DEVELOPMENT OF HARD-SOFT COATINGS FOR ENHANCED MACHINING PERFORMANCE EMPLOYING LARGE AREA FILTERED ARC DEPOSITION TECHNIQUE (CT77)

Phase II Final Report

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This Technical Report has been reviewed and is approved for publication.

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EXECUTIVE SUMMARY

This report describes the effort performed under Phase II part of the Edison Materials Technology (EMTEC) CT-77 program entitled “Development of Hard-Soft Coatings for Enhanced Machining Performance Employing Large Area Filtered Arc Deposition Technique”. Hard-soft coating has the potential to enhance the machining performance and reduce cost of the manufactured parts. In the Phase I part of this program, UES has utilized a patented and commercially viable large area filtered arc deposition (LAFAD) system for the development of hard and hard-soft coatings. Various hard coatings developed by the LAFAD technique were characterized and the machining performance of the tools coated with such coatings was evaluated. The coated tools, compared to uncoated ones, exhibited considerably enhanced tool life and hence enhanced machining performance. Soft lubricous coatings were also developed and their performance was evaluated in combination with hard coatings. Moreover, graded hard-soft coatings were developed and their machining performance was evaluated. Significant enhancement in the tool life was demonstrated with the graded hard-soft coating.

The development of hard and hard-soft coating was continued in Phase II. Few different types of hard-soft coating systems were developed using LAFAD technique and their machining performance was evaluated. The performance of the hard and hard-soft coatings was evaluated in machining operation involving commonly used ferrous materials as well as difficult to machine materials such as Hastelloy and titanium alloys. Considerable improvement in the tool life and machining performance was demonstrated.

In the recent past a new class of materials known as nanocomposites have been developed. The coatings of such materials have the attributes needed to meet the requirements for advanced wear resistant and tribological coatings for various applications including machining. In Phase II, a series of composite coatings were developed, characterized and their machining performance was evaluated.

In an effort to commercialize the developed coatings, in Phase II, besides local machine shops, various companies viz. Orton Ceramic, Westchester, OH, Nucor, Delphi, Arius Eickert and Kennametal were contacted. Arrangements were made to evaluate our coatings in their application (production environment). In some cases, for example, Orton Ceramic, Arius Eickert, and Kennametal, the performance of our coatings were compared to the currently used coatings. Our coating showed superior performance. Fixtures were also designed to hold more number of parts in one deposition run.

1.0 INTRODUCTION

1.1 OBJECTIVE

The overall objective of this program was the development and commercialization of hard and hard-soft coatings for enhanced performance of engineering materials for various applications including machining.

In accordance with the EMTEC goal, our ultimate aim was to commercialize the proposed technology. Thus in Phase II program substantial efforts were directed towards commercialization strategies.

1.2 BACKGROUND

The machining industry is constantly seeking ways to enhance performance (metal removal rate) and reduce cost of the manufactured parts. One way to enhance the machining performance is to utilize high speed machining. One of the problems associated with high speed machining is the high tool wear, leading to reduction in tool life. This is essentially due to the existence of higher cutting temperature generated between the tool tip and the component interface. Higher cutting temperature can also enhance the chemical reactivity between tool and certain work piece materials such as titanium (Ti). This can lead to higher chemical wear thereby further reducing the tool life. Lower tool life leads to frequent tool changes resulting in increased machine down time. This in turn reduces the overall productivity. Hence, it is essential to minimize the cutting temperature and/or the chemical reactivity.

Conventionally the cutting temperature is lowered by the use of metal-cutting fluids (coolants). However, due to safety and environmental concerns the use of coolant is not advisable. One of the alternatives to satisfy the demand for cost effective machining with reduced ecological impact is to employ high speed and/or dry machining technique. However, dry machining concept is still in its infancy and until it becomes a reality we must look for alternatives that will help us find ways to protect the tool from higher cutting temperature. This can be achieved through the exploitation of advanced surface coatings on cutting tools.

Hard wear resistant coatings such as TiN, TiCN, TiAlN, etc. provide overall improved tool life and better machining performance. Reduced temperature during machining can further enhance tool life and performance. Heat generation and therefore cutting temperature can be reduced by lowering the friction between the tool rake face and the chip, and the tool flank face and work piece interfaces. This can be accomplished by utilizing low friction coefficient soft lubricous coating on the tool along with the hard coating. Metal cutting and shaping operations done using soft MoS_2 (WS_2) coating on top of hard coating such as TiN, resulted in significant improvements in tool life, finish and productivity [1,2].

In the aforementioned coating scheme viz, deposition of soft coating on top of the hard coating, the interface between hard and soft coating is not cohesive. The abrupt nature of the interface may limit the durability of soft coating during machining. The durability of soft lubricious coating along with its beneficial effect can be enhanced by depositing a graded and mixed interface between hard and soft coatings. In the Phase I EMTEC program (CT77), we have employed a patented large area filtered arc deposition (LAFAD) technique to deposit hard and soft coatings. In Phase II, the deposition conditions were optimized to obtain a graded hard-soft coating. We have configured various combinations of hard and/or soft coatings and evaluated their performance in different machining applications including titanium machining.

Recently a concept of nano-composite coatings has been developed [3]. In composite coatings, materials having different properties are combined in a way that new and/or enhanced properties are created. One possibility is the development of nano composite coatings consisting of hard-nanocrystallites embedded in a soft low friction amorphous matrix. A schematic diagram of the crystalline/amorphous nanocomposite coating is shown in Figure 1. Recently, novel tough wear resistant nanocomposite coatings were developed that consist of crystalline hard transition metal nanocrystals (TiN, ZrN, TiC, TiB_2 etc.) embedded in an amorphous phase matrix (Ag, Cu, C etc.) [4]. Enhanced hardness and toughness of the composite coatings are due to hindering of the dislocation motion at the grain boundaries, impeding of crack propagation at the interface (hard-soft) and the grain boundary sliding. Moreover by choosing the appropriate chemistry of the composite coating friction can also be reduced. For example by the use of noble metal silver and C is appealing, since it is known to form coatings with good friction characteristics. In Phase II of this program, UES has also developed various nanocomposite coatings utilizing LAFAD system and their machining performance was evaluated.

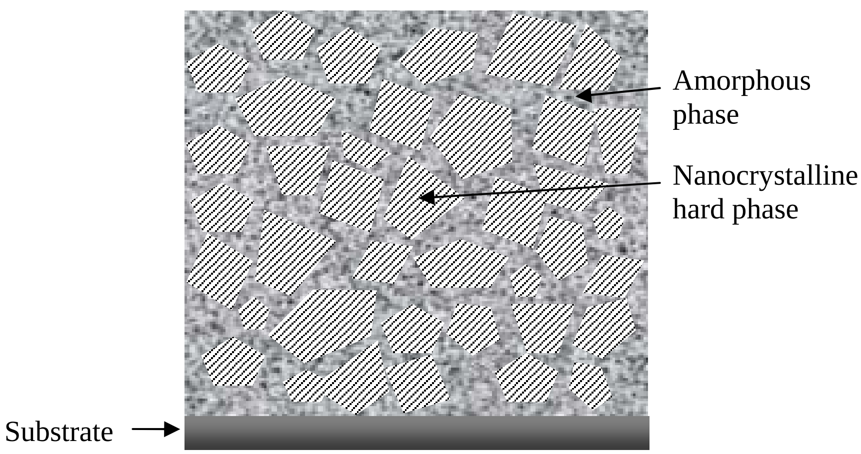


Figure 1. Proposed microstructure of the coating.

1.3 APPROACH

The Phase II project was an integrated effort involving the participation of a coating developer and provider (UES) and end user (machining industry). The major elements of the technical approach consisted of coating development at UES, coating characterization at UES, the University of Dayton Research Institute (UDRI) and Air Force Research Laboratory (AFRL) and machining performance evaluation of coatings at industry partners viz. Triangle Precision Inds, Harris Thomas Inds, Orton Ceramic, and Kennametal etc.

2.0 COATING DEPOSITION, CHARACTERIZATION AND MACHINING PERFORMANCE EVALUATION

2.1 COATING DEPOSITION SYSTEM

Physical vapor deposition (PVD) is an environmentally benign technique for coating deposition at relatively low substrate temperature. In any machining application, the coating must adhere strongly to the substrate and it must be highly dense. Such qualities of a coating in a PVD technique can be obtained by high ionization efficiency of the process. Among the known PVD methods, cathodic arc evaporation produces the highest degree of ionization. Currently the PVD coatings used in the machining industry are primarily based on direct cathodic arc deposition technology. A significant disadvantage of direct cathodic arc technique is the formation of droplets, also known as macroparticles, in the cathodic arc jets. The presence of macroparticles in the coating deleteriously influences critical properties of the coatings such as hardness, density and corrosion resistance. Also the macroparticles makes the coating rougher. The coating roughness can create problems in high precision surface finish machining.

In this program, large area filtered arc deposition system (LAFAD) was used to develop various coatings. In the following, salient features of the LAFAD system are described.

The LAFAD system is based on a patented cathodic arc deposition technology [5]. A schematic of the deposition system is shown in Figure 2. It consists of three key components: direct arc sources, large area filtered arc sources and auxiliary anode assembly. The LAFAD uses a rectangular plasma guide chamber with two rectangular coils installed on the opposite sides. Two cathodic arc sources with circular target are installed on the sidewalls of the plasma-guide chamber surrounded by rectangular deflecting coils. A dynamic magnetic field is applied to repel the arc from the edges, and imposes a transverse field at high switching frequency to make the arc run continuously around the target. The filtered arc sources allow the deposition of droplet free coatings by deflecting the plasma flow along the curvilinear magnetic lines of force toward the substrate, while the droplets having the straight trajectories, are captured on the baffles. The width of the plasma flow is about 10 inches and the height can be one to one and one half feet and more, which allows the coating of relatively large 3D machine tools. The filtered arc source can be used to operate in electron emission mode. It has been shown that filtered arc source can be used to extract highly energetic electrons, and used to ionize the gaseous plasma, such that a plasma envelope that completely surrounded the part can be created in the coating chamber. Using this technique, very high ion currents can be obtained as compared to other PVD techniques. When the substrate is strongly biased, significant ion implantation can be achieved. The two direct arc sources can be replaced by two 6-inch magnetron-sputtering guns. Thus the LAFAD system can be operated in a sputtering mode or in a hybrid mode of sputtering and filtered arc. The LAFAD system incorporates a patented auxiliary anode assembly to create dense plasma that surrounds the part. This anode design differs from the conventional PVD system that uses the coating system itself as the anode. The specially designed auxiliary anode greatly expands the capability and flexibility of the process.

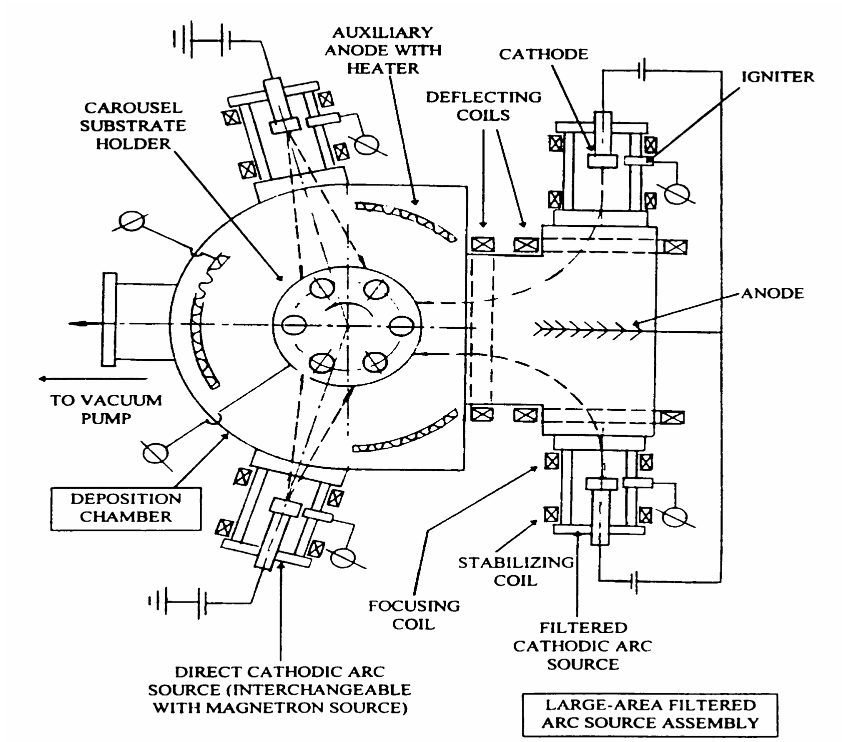


Figure 2. Schematic of the LAFAD System.

2.2 SUBSTRATE CLEANING: CHEMICAL AND PLASMA

To ensure good coating adhesion, substrates (coupons as well as tools) should be thoroughly degreased. For this an ultrasonic cleaning station (RAMCO) was installed in our laboratory. Some fixtures were designed to clean the tools without touching each other and the container wall. Substrates were initially degreased ultrasonically in blue gold (an alkaline solution) followed by water rinse. After water rinsing, the substrates were ultrasonically cleaned in acetone and isopropanol. Finally the substrates were blow dried in dry nitrogen.

To remove the thin surface oxide layer on the substrates, the dried substrates were further plasma cleaned in the deposition chamber prior to coating deposition. Plasma cleaning was accomplished by sputtering induced by energetic ion bombardment. Plasma cleaning was done in two steps. In the first step, the substrates were biased to ~-400V and sputter cleaning was accomplished in Ar discharge plasma. In the next step, sputter cleaning was accomplished by high-energy metal (Ti) ion bombard. In this step, substrates were biased to ~-1000V.

2.3 HARD COATINGS

2.3.1 <u>Deposition</u>

Various hard coatings such as mulitlayered Ti-TiN, TiCN, TiAlN, multilayered TiN-AlN, and multilayered Cr-CrN were developed utilizing LAFAD system with relevant arc sources. Substrates materials such as machine tools obtained from various industry partners and steel discs were acquired. The substrates were degreased in blue gold – an alkaline degreaser (PH: 12-13), followed by rinsing in water and isopropanol and blow dried with nitrogen.

Partially covered and highly polished Si pieces were also used as substrate materials. The cleaned substrates were mounted on the variable speed planetary substrate holder of the LAFAD system that can be biased with the either DC or RF power. The deposition chamber was initially evacuated to a base pressure of 10^{-3} Pa. The substrate temperature was raised to ~ 400°C. Initially the substrates were sputter cleaned in dense Ar plasma created by extracting electrons from the filtered arc sources using auxiliary anodes and keeping the deflecting magnetic field off. Final sputter cleaning was done in energetic Ti plasma. After sputter cleaning, a thin layer of Ti was deposited as a bond layer to enhance adhesion of the subsequent coating. Appropriate gases were used and the gas pressure in the chamber was kept in the range of 1.3×10^{-1} to 5×10^{-2} Pa.

For Ti-TiN multilayered coating, Ti plasma was extracted from the Ti arc sources; Ti layer was deposited in Ar atmosphere and TiN layer was deposited in nitrogen atmosphere.

TiCN coating was deposited by extracting Ti plasma from the arc sources in methane (CH_4) + nitrogen (N_2) atmosphere.

TiAlN was deposited either from a composite Ti-Al arc sources or from separate Ti and Al arc sources in N_2 atmosphere.

For Cr-CrN multilayered coating, Cr plasma was extracted from the Cr arc sources; Cr layer was deposited in Ar atmosphere and CrN layer was deposited in nitrogen atmosphere.

2.3.2 <u>Machining Performance Evaluation</u>

Machining performance of the coated tools was evaluated at our industrial partners such as Triangle Precision and Thaler Machining in their commercial production runs and compared with that of uncoated tools. In some cases, the performance of coated tools was also compared with the commercially available coatings. Some of the typical machining test results are given below.

Two sets of reamers (3 reamer in each set), were obtained from Thaler Machine Co. One set of reamers was coated with Ti-TiN multilayer and the other set with TiCN coating. The coated reamers were delivered to Thaler Machine Co. for their machining performance evaluation. The coated reamers were used for machining 1541 carbon steel. The three Ti/TiN coated reamers produced, 1330, 1400, and 1440 parts. The TiCN coated reamers produced parts in the range of 530-580. Thus it appears that in this particular machining operation Ti/TiN multilayer coating performed better than TiCN coating. Although the TiCN coated reamers produced more parts than the uncoated reamers, according to Mr. Mike Martin of Thaler Machine Company, the Ti/TiN coated reamers produced roughly three times more parts than the uncoated ones.

The machining performance of the TiAlN coated carbide end mills was evaluated at Triangle Precision Inds. The TiAlN coating was deposited from a composite Ti-Al target in nitrogen atmosphere. The work piece material was Hastelloy, a nickel based alloy. Hastealloy is considered as a hard to machine material. The machining (milling) conditions for uncoated and coated end mills are shown in Table 1. The number of parts produced by the three uncoated and by the first set of three coated end mills are also given in Table 1. It is clear that the TiAlN coating has doubled the life of the coated end mills. According to Tim Friedman of Triangle Precision, three commercially coated end mills produced 10, 9 and 12 parts under identical machining conditions. The other set of three TiAlN coated end mills produced 13, 20 and 21 parts under machining conditions given in Table 1.

Table 1. Machining Conditions for Uncoated, TiAlN and Commercially Coated End Mills

Parameter	**Uncoated**	**TiAlN Coated**	**Commercial Coating**
Speed (RPM, SFM)	900, 118	900, 118	900, 118
Feed (ipm)	8	8	8
Depth of Cut (inch)	.400	.400	.400
Length of Cut (inch)	24	24	24
Width of Cut (inch)	.150	.150	.150
# of Parts Produced	6, 5, 8	12, 16, 15	10, 9, 12

The machining performance of the TiAlN coating deposited on 0.25 inch diameter carbide end mills with separate Ti and Al arc sources was evaluated in two different milling operations at Triangle Precision Inds. For comparison purpose the machining performance of uncoated end mills and the end mills coated with commercial (Comm) coating was also evaluated under identical conditions. The two machining conditions for uncoated, coated (UES) and commercially coated end mills are shown in Table 2 and 3. The TiAlN coated tools produced more than two times the number of parts produced by uncoated tools. TiAlN coated tools also produced either equal or more number of parts than the tools coated with commercial coating.

Table 2. Machining Conditions for Uncoated, TiAlN and Commercially Coated End Mills

	Speed SFM	Feed Inch	Dept of Cut - Inch	Length of Cut-Inch	Width of Cut-Inch	# of Parts
Uncoated	250	12	0.3	8.8	0.02	22
Coated (UES)	250	12	0.3	8.8	0.02	47
Coated (Comm)	250	12	0.3	8.8	0.02	46

Table 3. Machining Conditions for Uncoated, TiAlN and Commercially Coated End Mills

	Speed SFM	Feed Inch	Dept of Cut - Inch	Length of Cut-Inch	Width of Cut-Inch	# of Parts
Uncoated	250	12	0.3	6.7	0.02	28
Coated (UES)	250	12	0.3	6.7	0.02	70
Coated (Comm)	250	12	0.3	6.7	0.02	65

2.4 HARD –SOFT COATINGS

2.4.1 TiN-WS_2 (MoS_2) Coating

Generally, the soft coatings are deposited under conditions different from that of the hard coatings and therefore it is essential to determine the characteristics of the soft coatings obtained under the condition required for hard coating. One of the proposed approaches to deposit hard-soft coating was to utilize a hybrid arc plus magnetron sputtering technique. Sputter deposition of soft WS_2 coating is usually done in Ar atmosphere, whereas hard TiN coating is deposited from highly ionized Ti plasma from filtered arc source in nitrogen atmosphere. Thus it was planned to evaluate the soft WS_2 coating deposited under gaseous (Ar, Ar/N_2), and gaseous plus metal (Ti) plasma conditions. In Phase I we had deposited and characterized the friction behavior of soft WS_2 coating in gaseous Ar, Ar-N_2 (50/50, 80/20, 90/10) plasma. The friction coefficient and chemical composition of the coatings are summarized in Table 4. It is clear from the Table 4 that the nitrogen content in the coating increases with increase in the nitrogen partial pressure. Also higher nitrogen and concomitantly lower sulfur content in the coating provides higher friction. At Ar/N_2 pressure ratio of 90/10, the friction coefficient of the coating was found to be close to that of the WS_2 coating deposited in pure Ar atmosphere. With this result in hand effort was directed to determine the effect of Ti plasma on the chemical composition and friction characteristic of the WS_2 coating deposited in Ar and Ar/N_2 atmosphere. Specifically WS_2 coating was deposited in Ar+Ti plasma and in Ar/N_2 (90/10) + Ti plasma.

The chemical composition of the deposited coatings was determined by Auger electron spectroscopy (AES) in combination with Ar ion sputtering. Friction profiles of the coatings were determined by pin-on-disc technique. In a pin-on-disc technique, a quarter inch (0.25 inch) diameter steel (M50) ball was used as the pin and 100 gm load was used to provide the initial Hertzian stress of 0.61 GPa based on steel on steel configuration. A sliding speed of ~ 0.1 m/sec was used. Friction tests were conducted in room atmosphere with relative humidity (RH) ~ 50%.

Figures 3a and b represents the AES profiles of the coating deposited in Ar + Ti and in Ar/N_2 + Ti plasma. The friction profiles of these coatings are shown in Figures 4a and b. The results of the composition analysis and friction coefficient are compiled in Table 5. Comparing the chemical composition data listed in Table 4 and Table 5, we found that the addition of Ti filtered arc plasma reduced overall percentage of W and S level in the coating in Ar atmosphere. Further reduction in W and S level was observed when Ti filtered arc plasma was introduced in Ar/N_2 (90/10) atmosphere. Impurities such as carbon and oxygen were also found in the coating. The friction coefficient in Ar/N_2 +Ti plasma was relatively lower ~0.24. It should be mentioned that even with the relatively low level of S and W in the hard-soft coating the reamers coated with such coating performed two times better than that with commercial coating [6].

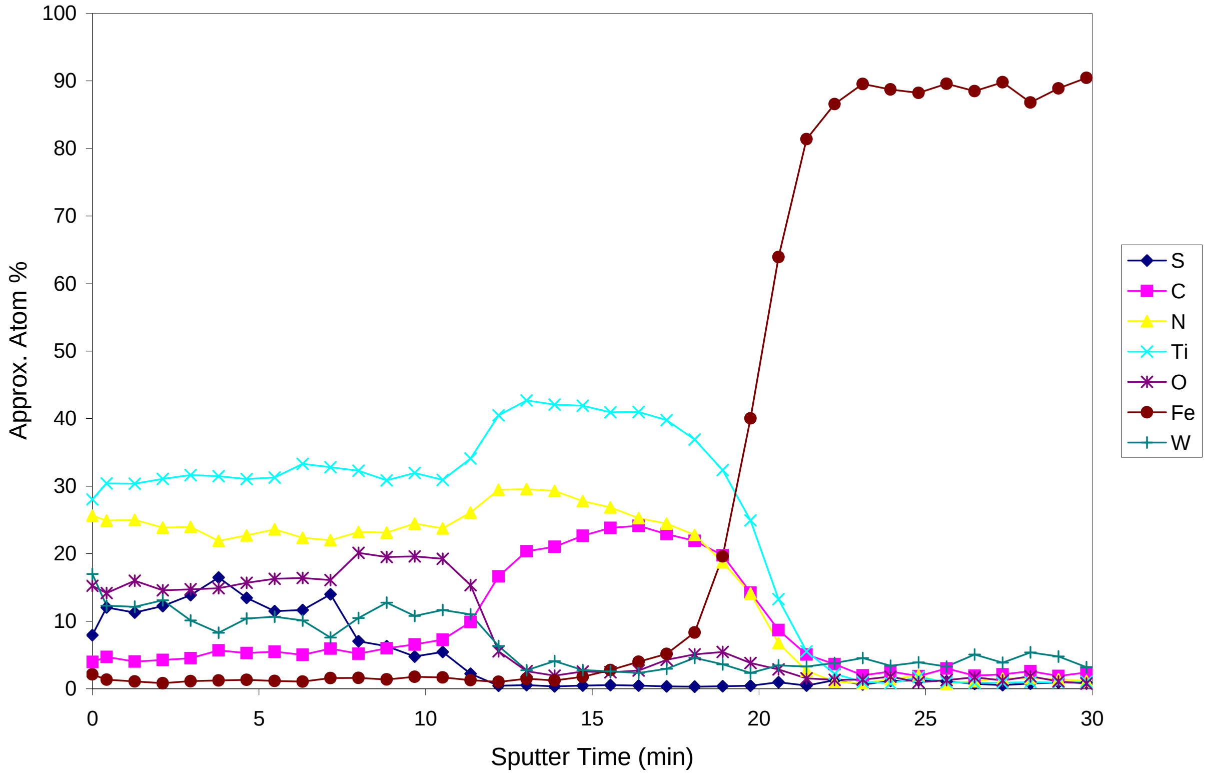


Figure 3a. AES profile of W-S coating in Ar+Ti plasma.

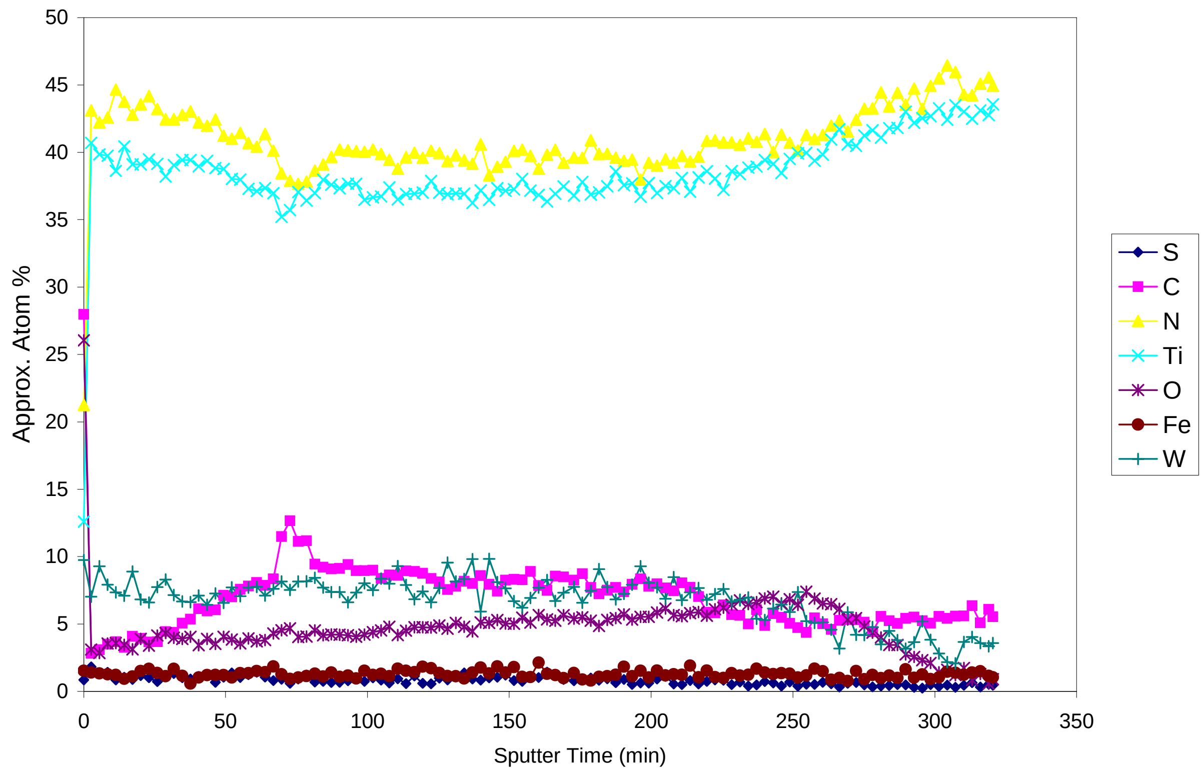


Figure 3b. AES profile of W-S coating in Ar/N_2 (90/10) + Ti plasma.

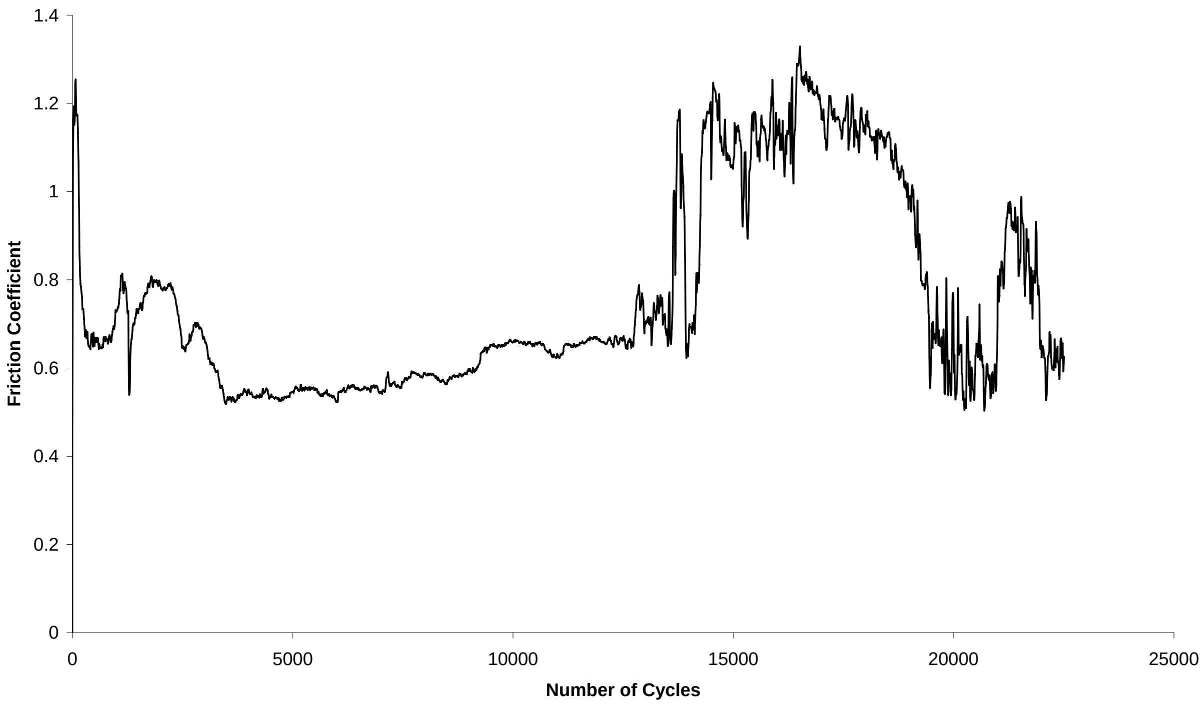


Figure 4a. Friction force profile of W-S coating in Ar+Ti plasma.

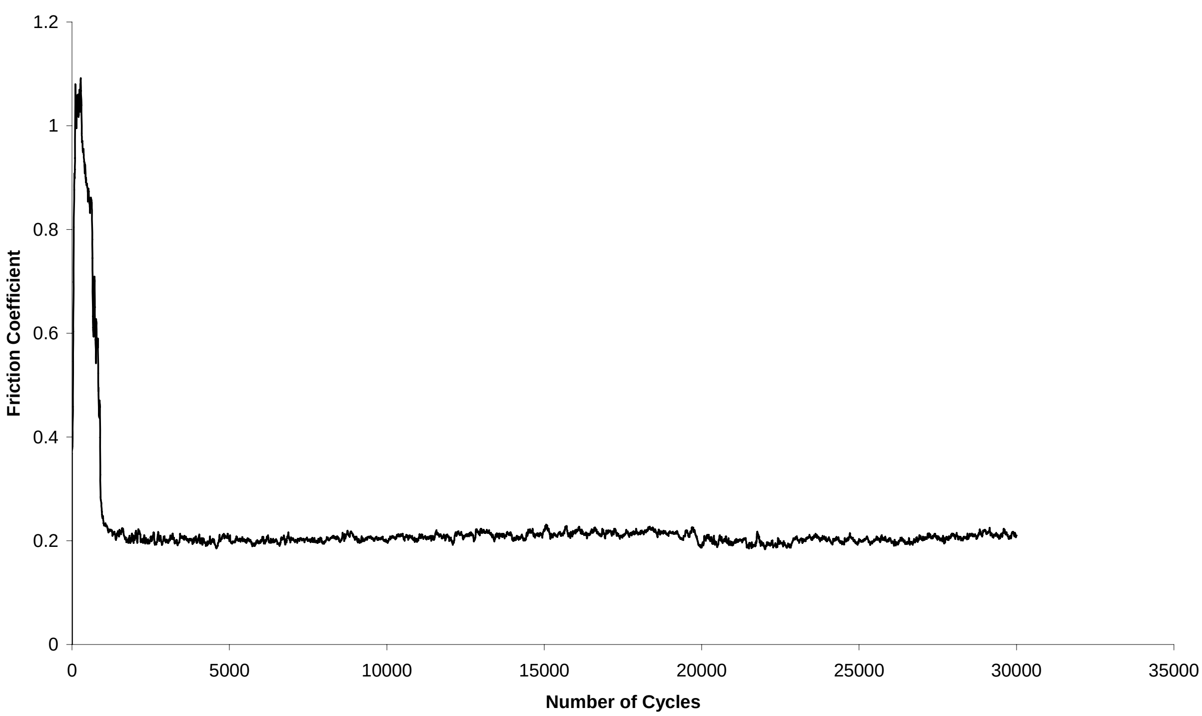


Figure 4b. Friction force profile of W-S coating in Ar/N_2 (90/10) +Ti plasma.

Table 4. Composition and Friction Coefficients of W-S Coatings in Various Gaseous Atmospheres.

Coating Run #	Atmosphere	Pressure	Arc Source (Ti) On/Off	Magnetic Field	Magnetron (WS_2) On/Off (Power)	Composition AES	Friction Coefficient
470	**Ar**	**1-2 Pa**	**On**	**Off**	**On (1KW)**	**S:W::48:35**	**0.13-0.15**
471	**Ar/N_2 50/50**	**1-2 Pa**	**On**	**Off**	**On (1KW)**	**W:S:N::50:9:38**	**0.77-1**
473	**Ar/N_2 80/20**	**1-2 Pa**	**On**	**Off**	**On (1KW)**	**-**	**0.6**
472	**Ar/N_2 90/10**	**1-2 Pa**	**On**	**Off**	**On (1KW)**	**W:S:N::50:30:8**	**0.15**

Table 5. Composition and Friction Coefficients of W-S Coatings in Gaseous and Metal (Ti) Plasma.

Coating Run #	Atmosphere	Pressure	Arc Source (Ti) On/Off	Magnetic Field	Magnetron (WS_2) On/Off (Power)	Composition AES	Friction Coefficient
625	**Ar**	**1-2 Pa**	**On**	**On**	**On (1KW)**	**Ti:W:S::30:15:12 Ti/W=2**	**0.6**
597	**Ar/N_2 50/50**	**1-2 Pa**	**On**	**On**	**On (1KW)**	**Ti:N:W:S::39:40:8:1 Ti/W=4.9**	**0.24**

To enhance the W and S level in the coating, it was decided to deposit WS_2 by arc evaporation of W in hydrogen sulfide (H_2S) atmosphere. It was found that with our existing power supply, it is very difficult to keep the arc going on the W target. However, we were able to deposit a thin film of WS_2. A friction profile of such film was generated by the pin-on-disc technique under the conditions mentioned before and a friction coefficient of ~0.12 was obtained (see Figure 5). The thinner WS_2 film broke down after 1000 cycles resulting in higher friction. This experiment clearly demonstrated the validity of the vacuum arc technique for depositing WS_2 film. The arc instability on the target could be related with the high atomic number (74) of W. Perhaps higher current is needed to sustain the arc on the W source that requires a power supply with higher current capability. The other concern was the rather toxic nature of the H_2S gas.

It was thought that the performance of the hard-soft coating can be further enhanced by retaining right amount of S in the coating. Thus it was decided to develop a process to obtain hard-soft coating having right amount of S. Due to easy availability, a MoS_2 target was selected instead of WS_2. It should be mentioned that the friction coefficient of MoS_2 and WS_2 is about the same. Initially the MoS_2 coating was deposited utilizing a MoS_2 disc as an arc source in the LAFAD system. The friction coefficient of MoS_2 coating was determined by ball-on-disc technique. A 0.25 inch diameter steel (M50) ball was used as the ball with a 100 gm normal load and a linear speed of 0.1 m/sec in contact with rotating 1 inch diameter MoS_2 coated disc in laboratory atmosphere (RH ~ 58%). Figure 6 shows the friction coefficient profile of MoS_2 coating indicating very low (~ < 0.1) friction coefficient.

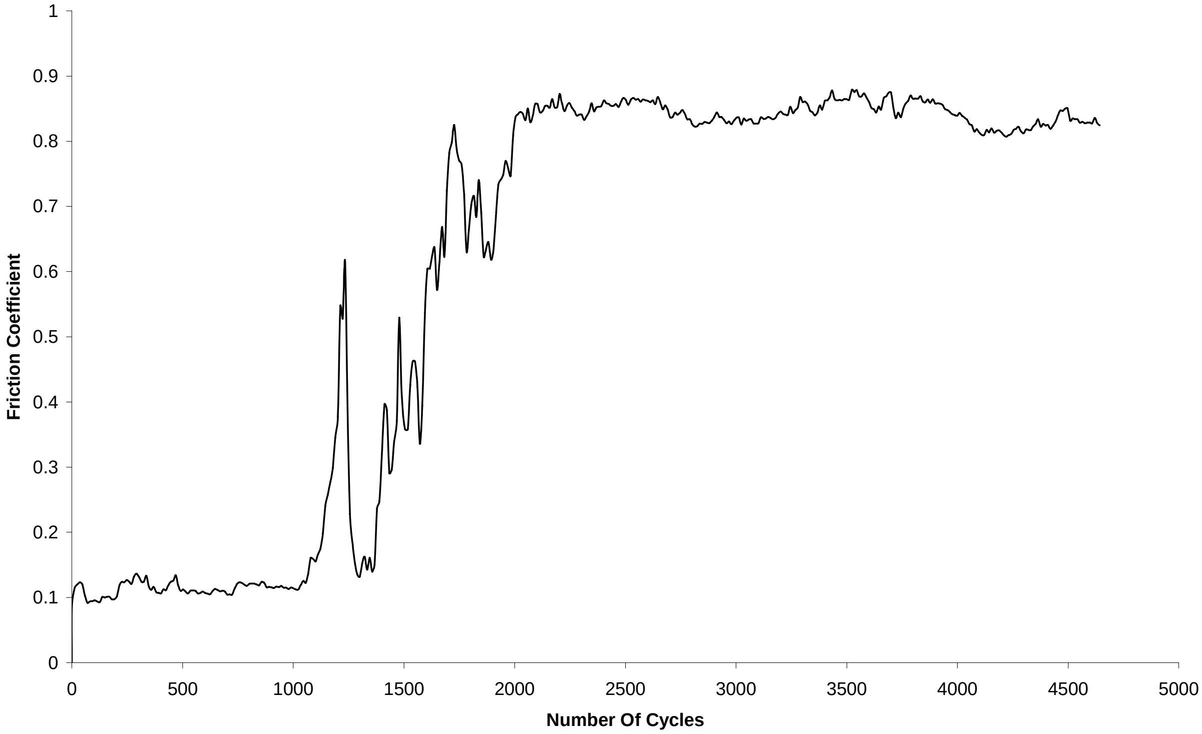


Figure 5. Friction force profile of WS_2 coating deposited by arc evaporation of W in H_2S atmostphere.

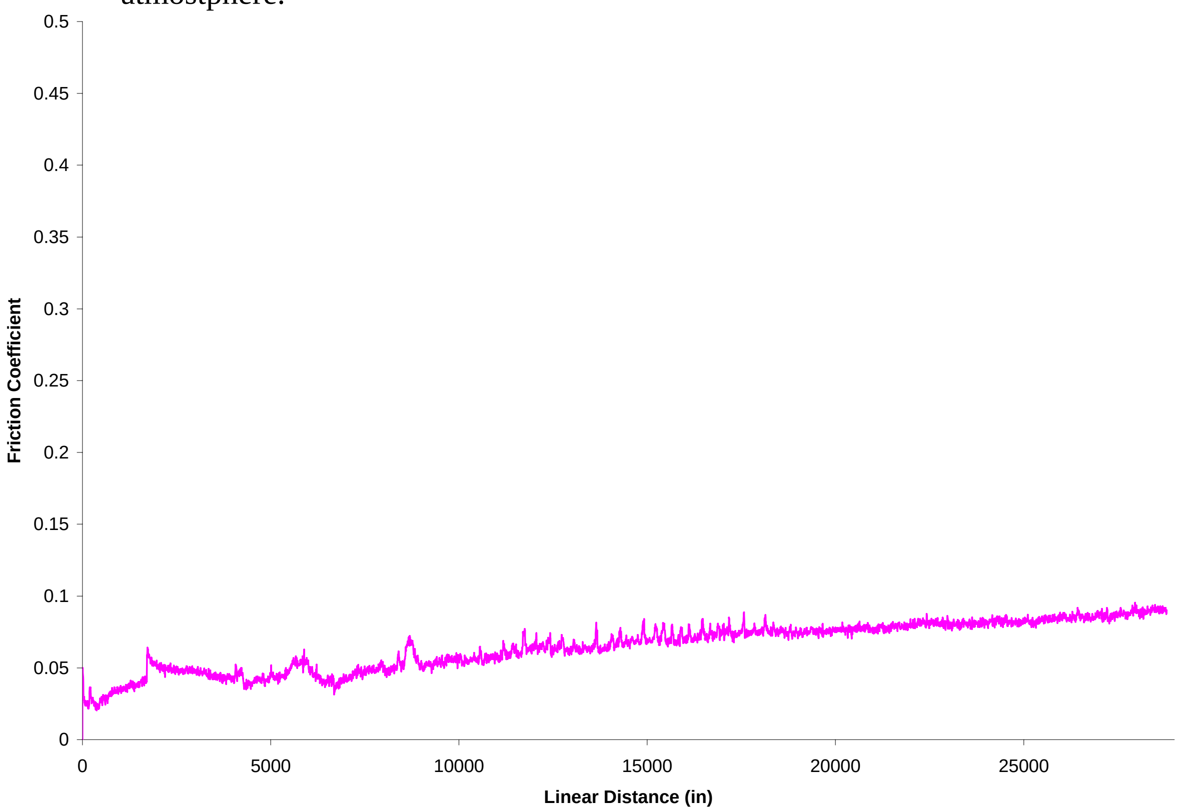


Figure 6. Friction coefficient of MoS_2 coating.

A hard-soft TiN-MoS_2 coating was also deposited on top of a hard TiN coating. TiN-MoS_2 coating was deposited by operating both Ti and MoS_2 arc sources in nitrogen atmosphere. Figure 7 shows the friction coefficient profile of this coating. The hard-soft coating exhibited a steady state friction coefficient of 0.3 – 0.35 which is lower than hard TiN coating (0.6-0.8) and higher than soft MoS_2 coating (~0.1). The sulfur content of this coating was determined by Auger electron spectroscopy (AES) and found to be in the range of 5-20 at% (Figure 8). Mo was found to be in the range of 5-8 at %. A large amount of C was detected, the source of which was identified as the AES system that was operating under relatively poor vacuum conditions. The variation of Mo and S content throughout the coating could be due to the lack of randomness in the arc movement over the MoS_2 arc target.

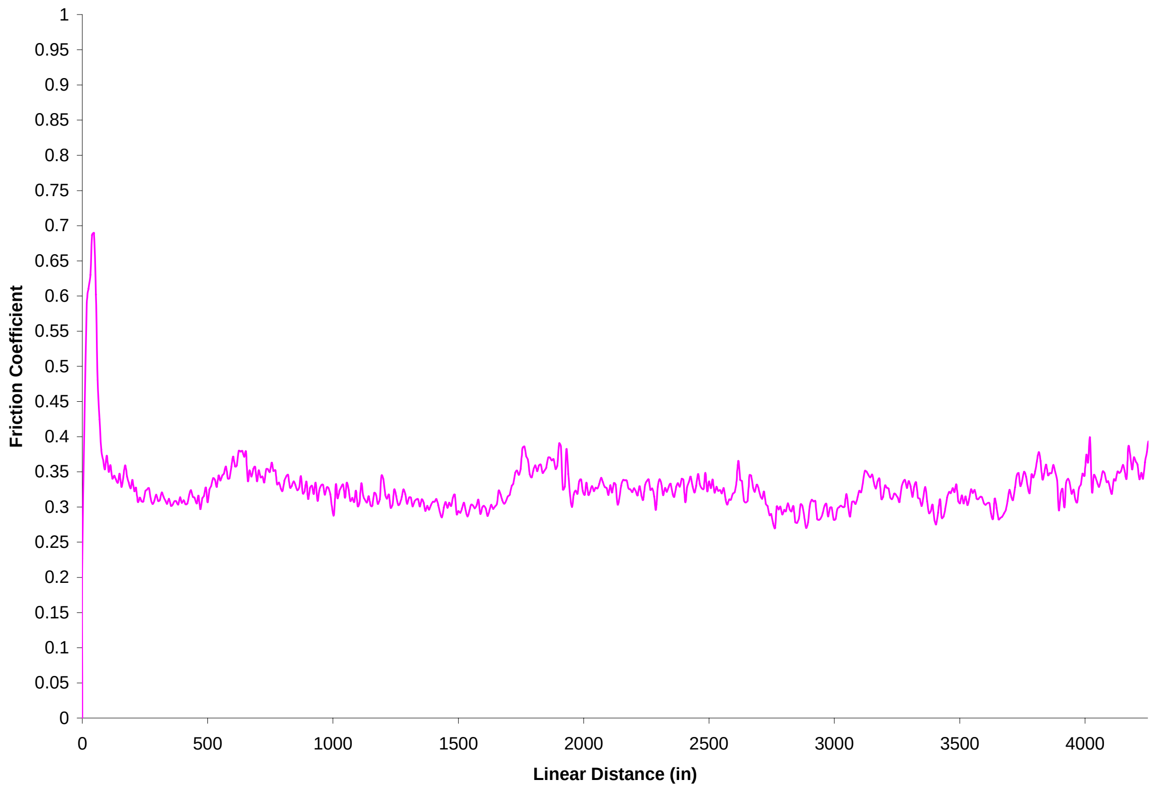


Figure 7. Friction coefficient of hard-soft (TiN-MoS_2) coating.

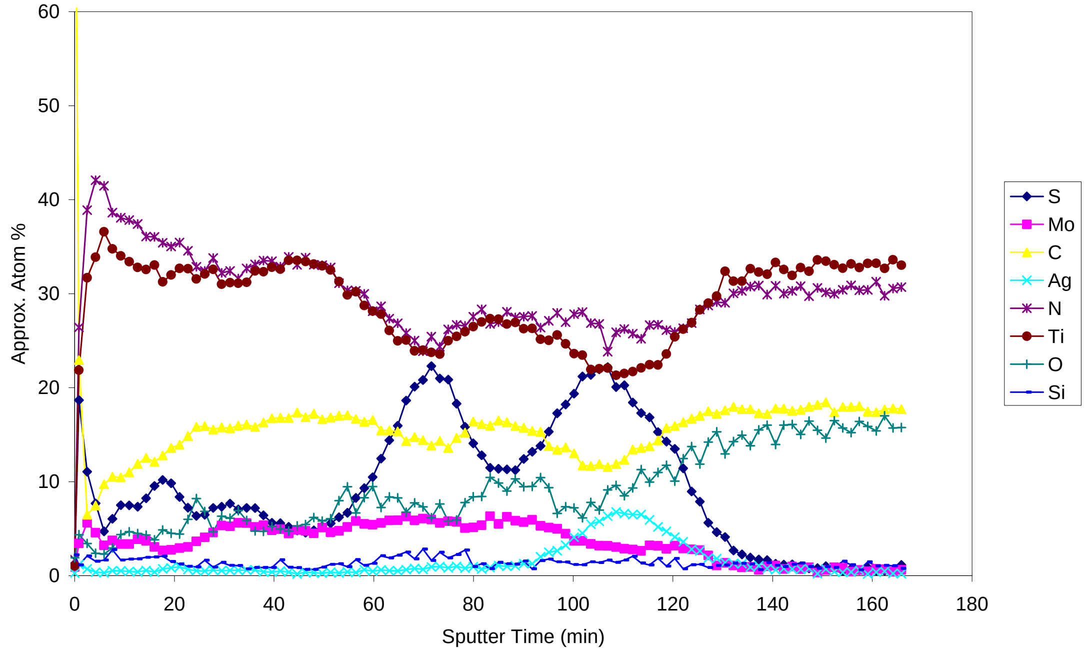


Figure 8. AES depth profile of TiN-MoS_2 coating deposited by arc process.

The issue of depositing consistent TiN-WS_2 (MoS_2) hard-soft coating prompted us to explore the possibility of composite coatings for machining applications. In this program composite coatings such as TiN-Ag, TiC+C, TiN (MoN)-Cu and TiN-SiN coatings were developed and evaluated. The TiN-Ag and TiC+C composite systems are interesting because Ag and C are known lubricants and therefore these coatings can also be considered as hard-soft coatings.

2.5 COMPOSITE COATINGS

2.5.1 <u>TiN+Ag Coating</u>

To develop TiN-Ag coating a composite arc target was fabricated in the following manner. The composite target was prepared by drilling cavities in the Ti arc target and filling them with Ag slugs. A photograph of the composite target is shown in Figure 9.

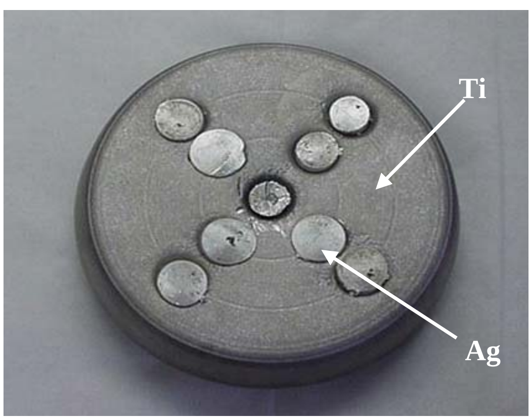


Figure 9. A photograph of the composite target.

In the first deposition run (#866) with composite arc target, the substrates (steel disc, Si pieces) were plasma cleaned in Ar ion plasma followed by a thin Ti layer deposition as bond layer. Finally the Ag based coating was deposited by activating the composite target in N_2 atmosphere. It was observed that during operation of the composite target, at a given time, the arc was mostly confined around one of the holes filled with Ag plug. Occasionally the arc hopped to other holes as well. Friction coefficient of the deposited coating was determined by pin-on-disc technique. In this technique a quarter inch (0.25 inch) diameter steel (M50) ball was used as the pin and the coated steel disc was used as disc. A 100 gm load was used to provide the initial Hertzian stress of 0.61 GPa based upon steel on steel configuration. A sliding speed of ~0.1 m/sec was used. Friction test was conducted at room atmosphere with relative humidity of ~ 40-50%. Figure 10 represents the friction profile of the coating. After initial break-in period the friction coefficient was stabilized around ~0.33. The test was deliberately stopped after 30 minutes. The steady friction profile for over 11000 cycles indicates the dense and adherent nature of the coating.

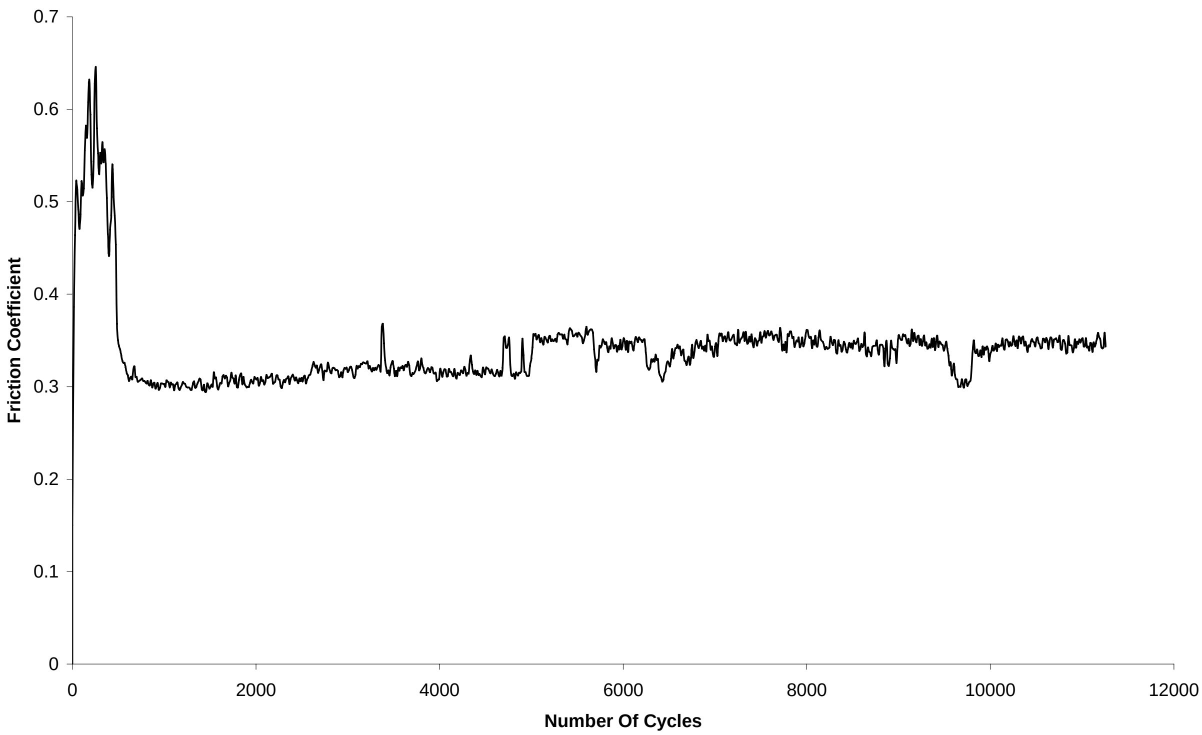


Figure 10. Friction force profile of Ag based coating in run #866.

A second deposition run (#867) was made under conditions identical to first deposition run. This run was made to duplicate the friction characteristics of the Ag coating found in the last run. Figure 11 shows the friction profile of the coating deposited in second run. Similarity in the friction profiles between 1st and 2nd run, indicate the robustness of the composite target. It should be mentioned that although in both deposition runs, the arc was confined near the hole filled with Ag plug, it is possible that some of the Ti may also have been evaporated and deposited in the coating as TiN.

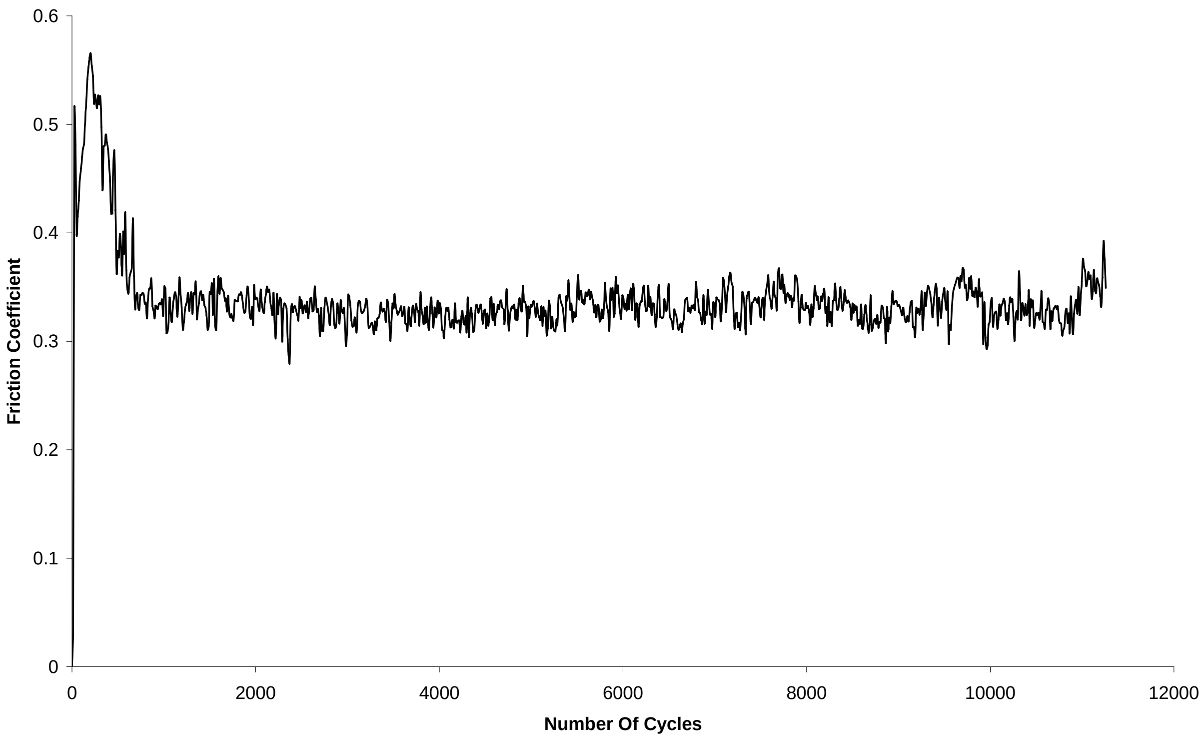


Figure 11. Friction force profile of Ag based coating in run #867.

Encouraged by the friction data, a third deposition run (#868) was made. In this run attempt was made to deposit a hard coating first followed by a hard-soft coating. Specifically, after the usual plasma cleaning and bond coat deposition steps, a hard Ti/TiN based multilayered coating was deposited followed by the mixed hard-soft (TiN-Ag based) coating. The mixed hard-soft coating was deposited by activating both a Ti arc target and the composite target in N_2 atmosphere. On top of the hard-soft coating an Ag based coating was deposited by only activating the composite target in N_2 atmosphere. Figure 12 represents the friction profile for the coating deposited in third run. As expected the initial friction coefficient was similar (~0.33) to that observed in first (#866) and second (#867) deposition runs. After ~ 9000 cycles the friction coefficient went up to (~0.65). It is speculated that the higher friction coefficient is associated with the underlying hard coating.

Attempts were made to control the amount of Ag in the TiN-Ag coating by varying the arc current in the composite arc source. Three deposition runs (#955, #956, and #957) were made with Ti-Ag composite target as a direct arc source (#0) in combination with a pure Ti also as a direct arc source (#3). In run #963, the composite Ti-Ag target was used as a filtered arc source (#2).

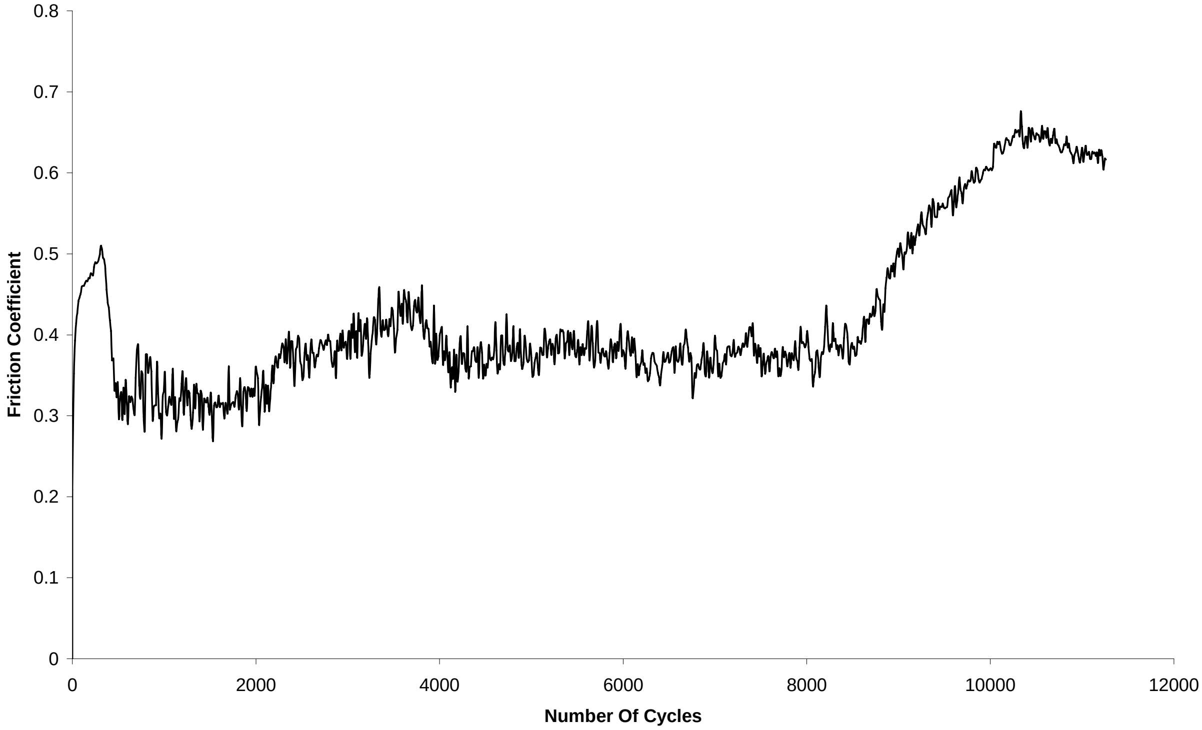


Figure 12. Friction force profile of Ag based coating in run #868.

In run # 955, #956, and #957 the arc currents in Ti-Ag were kept at 80, 40 and 60 amp respectively. The arc current in the other pure Ti direct arc source (#3) was kept at 80 amps in all the three runs. The energy dispersive x-ray spectra (EDS) spectra of the coatings deposited in the three runs are shown in Figures 13-15. The peaks corresponding to Ti and Ag in the coating were clearly observed. The Fe peak is from the steel substrate. The Ag percentage in the coating was calculated from the standard software program. The deposition configuration and the Ag percentage in the coatings are shown in Table 6. The high percentage of Ag observed in run #955 indicates that from the composite target mostly Ag evaporates. It is clear from the Table 6 that lower arc current in the composite target provides less Ag in the coating. In other words the percentage of Ag in the coating can be controlled by manipulating the arc current in the composite target.

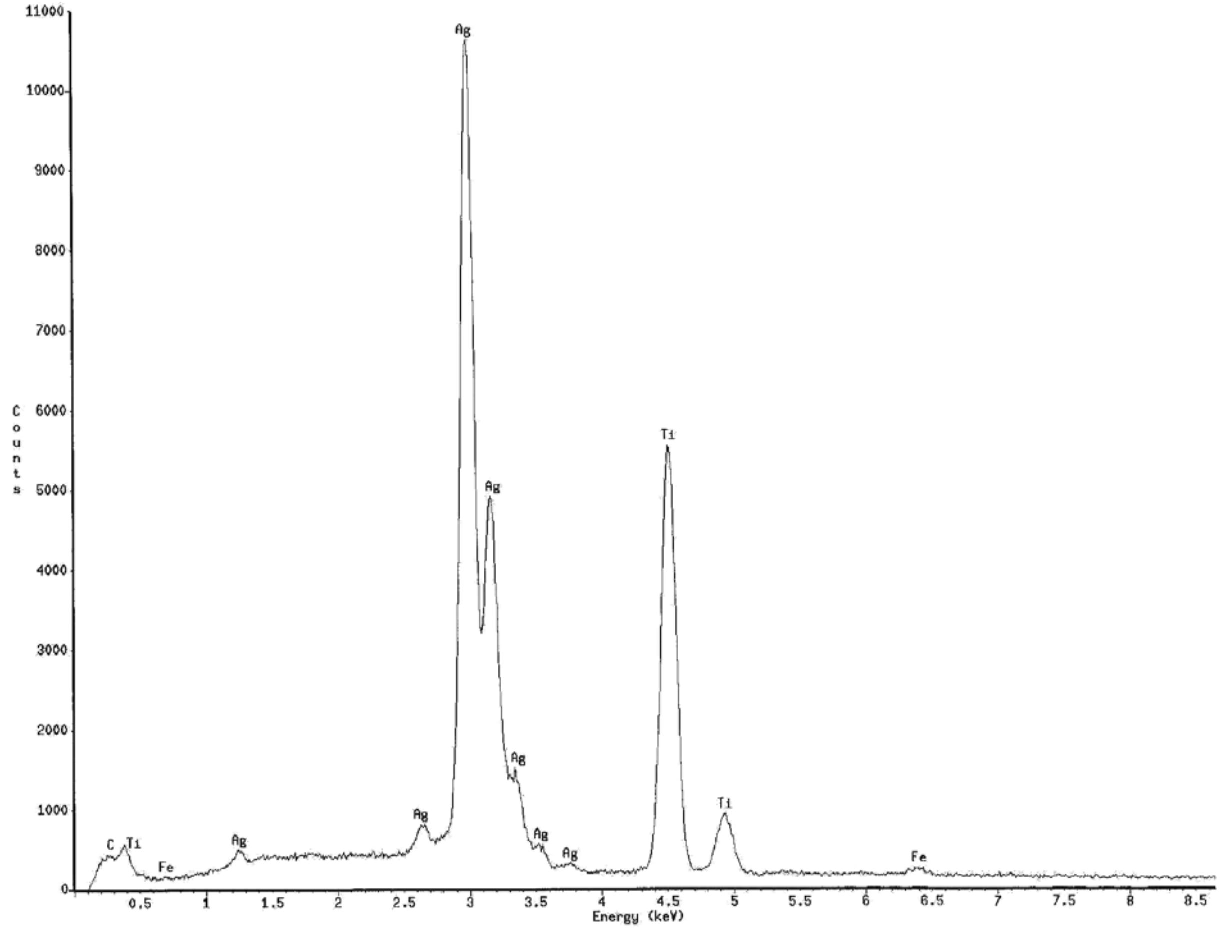


Figure 13. EDS spectrum of the coating deposited in run #955.

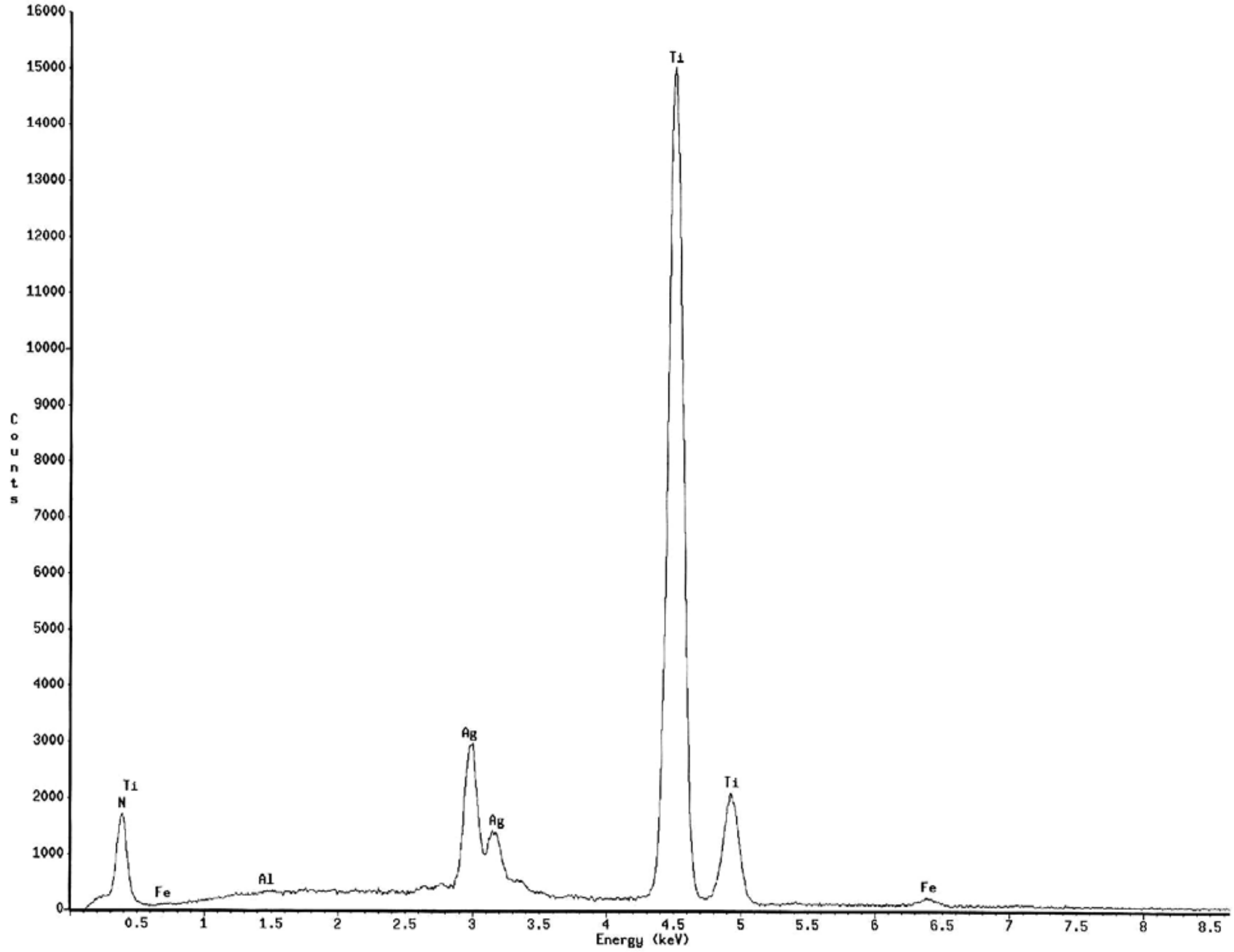


Figure 14. EDS spectrum of the coating deposited in run #956.

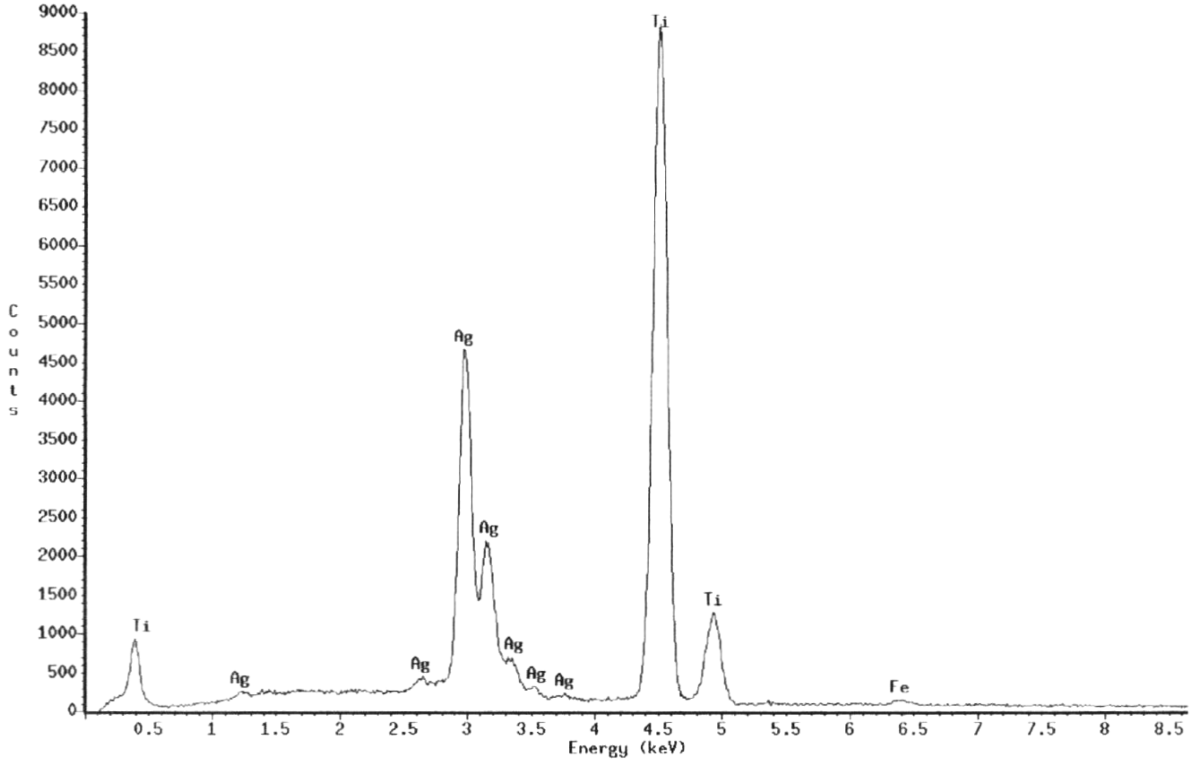


Figure 15. EDS spectrum of the coating deposited in run #957.

Table 6. Deposition Configuration and Ag Percentage in the Coating

Run #	Direct Arc Source #0	Direct Arc Source #3	Filtered Arc Sources #1	Filtered Arc Sources #2	Arc Current in Ti-Ag Source (Amp)	Ag (at %)
955	Ti-Ag	Ti			80	48%
956	Ti-Ag	Ti			40	8%
957	Ti-Ag	Ti			60	22%
963		Ti		Ti-Ag	60	1%

It should be mentioned that, a certain level of arc current is needed for the arc to run properly on the face of the target. Thus the arc current cannot be lowered beyond a certain level. To further lower the Ag content in the coating, it was decided to run the composite target from the filtered arc source. The run #963 was made with Ti-Ag target as a filtered arc source (#2). In this run a Ti direct arc source was also utilized. The arc current in the Ti-Ag and Ti targets were kept at 60 and 80 amp respectively. The EDS spectrum of the coating from run # 963 is shown in Figure 16. The Ag percentage in the coating was found to be very low (~1%, see Table 6). Such low concentration of Ag in the coating could be related with the filtering of the Ag macroparticle from the plasma. The EDS spectrum of the coating from a control sample (run #964) having only TiN coating is shown in Figure 17. As expected, no indication of Ag was found in the control sample. Thus it is possible to control the Ag content in the coating through manipulation of the arc current in the composite target.

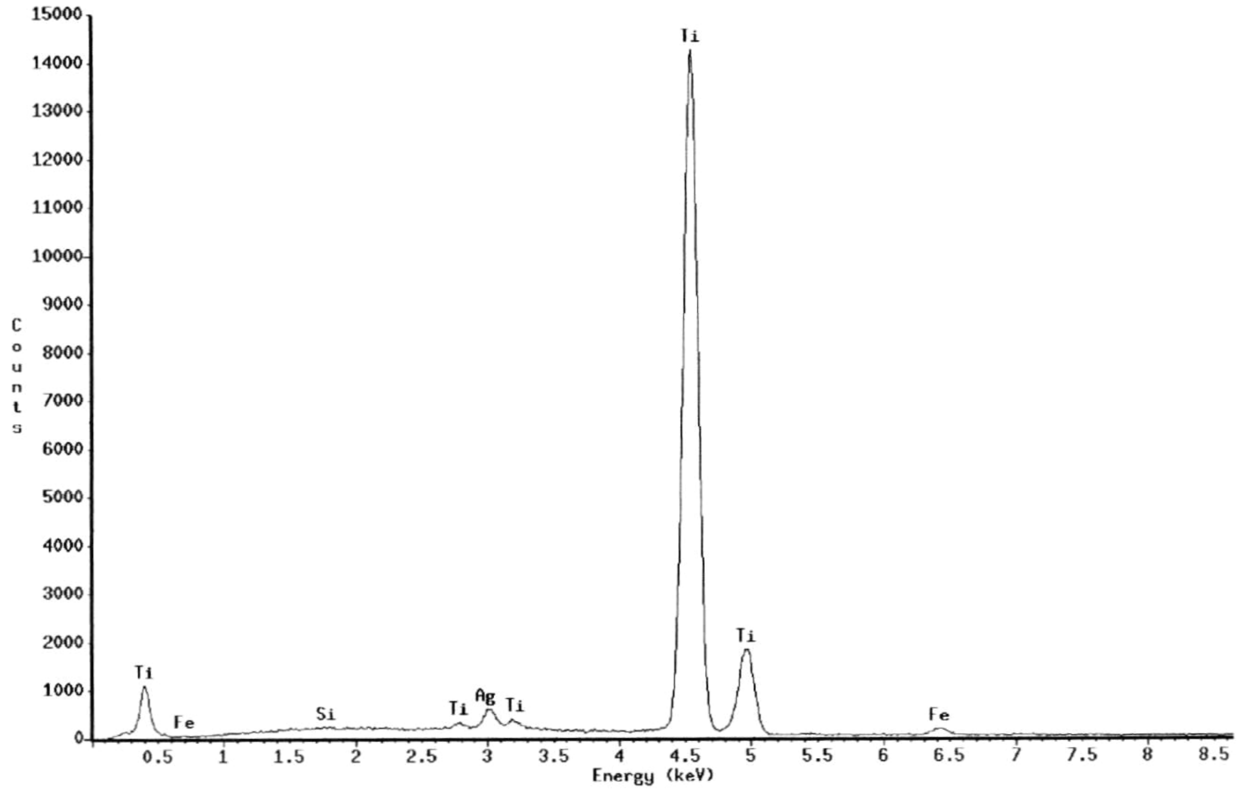


Figure 16. EDS spectrum of the coating deposited in run #963.

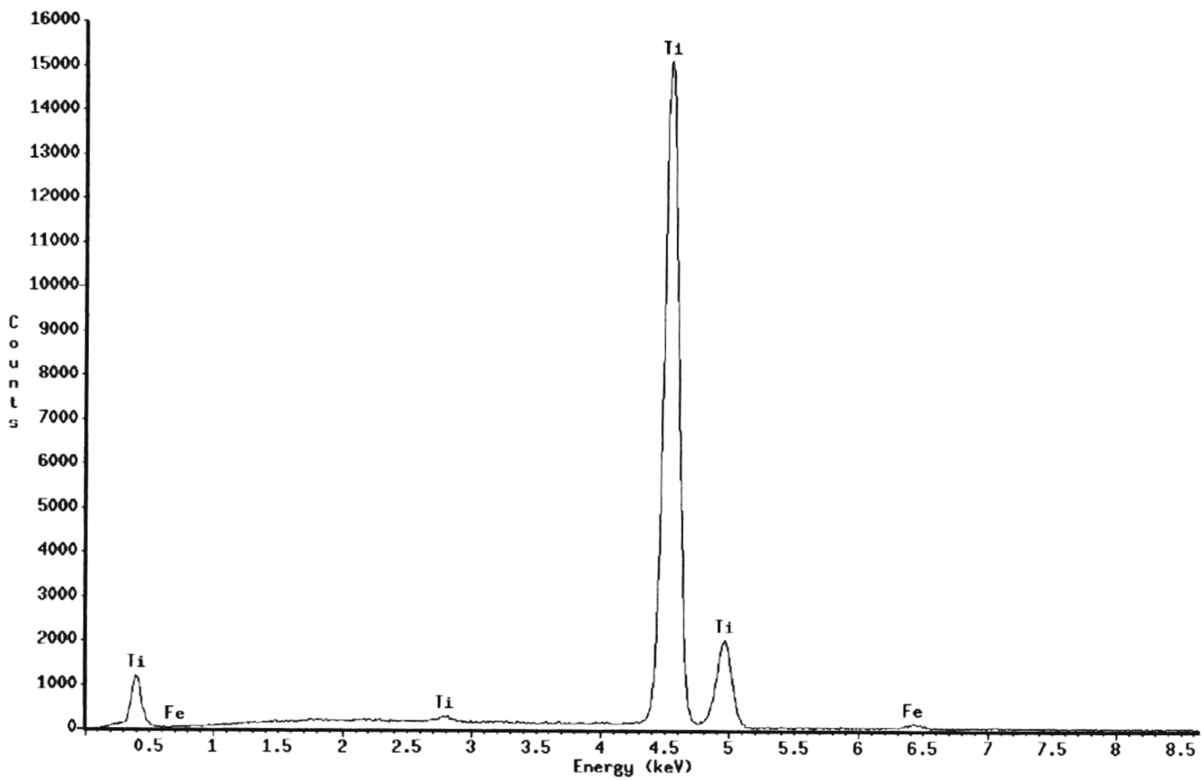


Figure 17. EDS spectrum of the coating deposited in run #964.

The performance of the TiN-Ag coated end mills of two different sizes viz. 0.5 inch and 0.109 inch diameter were evaluated and compared with that of the uncoated end mills at Triangle Precision Inds. The milling conditions, shown in Table 7, for coated and uncoated 0.5 inch diameter end mills are shown in Table 7. The coated 0.5 inch diameter end mills produced 10 to 13 parts compared to the 4 parts by uncoated end mills. The coated 0.109 inch diameter end mills produced 4 parts compared to only 2 parts by uncoated end mills.

Table 7. Milling Conditions for Uncoated and Coated (Ag based hard-soft coating) ½" End Mills

	Uncoated End Mill	Coated End Mill
Speed	5900 rpm	5900 rpm
Feed (SFM)	F6	F6
Depth of Cut	0.585 in.	0.585 in.
Tool Diameter	0.5 in.	0.5 in.
Parts Produced	4 parts	10-13 parts

The 1/ 8 inch diameter coated end mill produced a maximum of up to eight parts. According to the machinist, Mr. Ryan Miller, this coating produced more parts than the commercially available black-coated Melin end mills.

2.5.2 TiC+C Coating

A carbon based hard (TiC)-soft (C) coating was also fabricated. This coating was produced by activating Ti arc sources in the presence of CH_4 atmosphere. A typical friction profile of the TiC+C coating is shown in Figure 18 with a friction coefficient of ~0.12. The microstructure of the TiC+C film was analyzed by transmission electron microscopy (TEM). A selected area diffraction pattern and a corresponding dark field micrograph are shown in Figures 19a and 19b respectively. Based on the TEM analysis, the coating was found to consist of nano-crystalline grain (~20-30nm) TiC particles. The friction coefficient, hardness and toughness of the TiC+C coating can be manipulated by varying the carbon content in the coating.

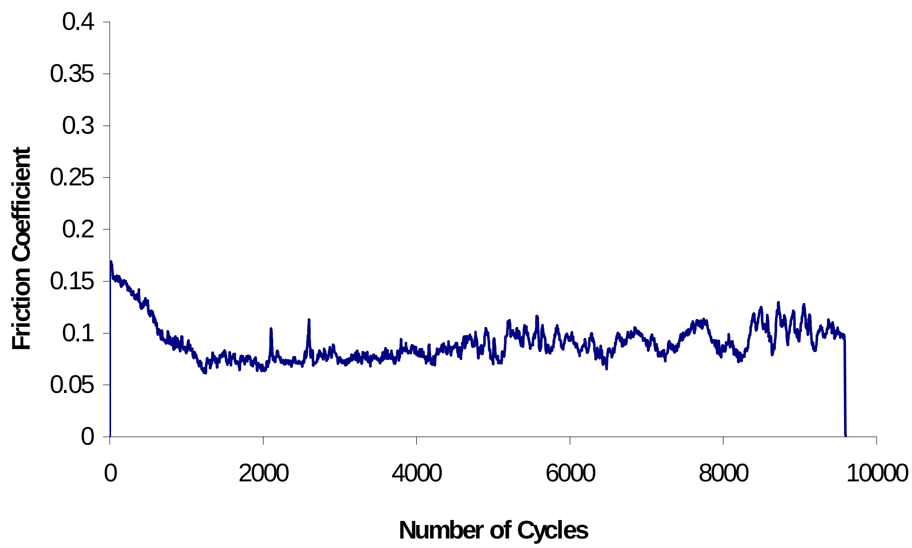
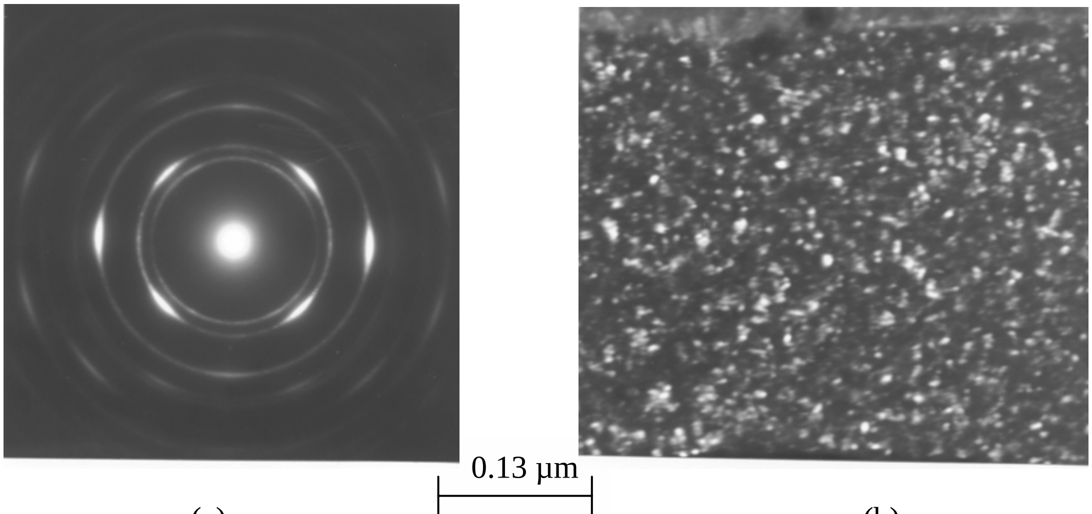


Figure 18. Friction coefficient vs. number of cycles for TiC+C coating.



(a) (b)

Figure 19. (a) SAD pattern, and (b) Dark field micrograph of TiC + C coating.

2.5.3 Mo-N+Cu Coating

Another approach to enhance the tool life is to develop a harder wear resistant coating whose oxidation product is lubricous at high temperature. Thus an appropriate coating material can be selected that undergoes oxidation during machining producing lubricous oxide, and therefore reduce friction [7,8]. With this thought in mind, in this Phase II project, MoN based composite coatings were also developed. It should be mentioned that the oxides of molybdenum are known high temperature lubricants.

The following procedure was used for developing MoN based coatings. Highly polished steel discs were thoroughly degreased ultrasonically in blue gold and isopropanol and blow dried in nitrogen. The cleaned discs together with few Si pieces were loaded in the large area filtered arc deposition (LAFAD) system and the system was evacuated to a base pressure of ~ 10^{-3} Pa. Initially the parts were sputter cleaned in Ar plasma. A metallic bond (Cr) coating was deposited on top of the sputter-cleaned parts. Initially a base line Mo-N coating was deposited by turning on a Mo arc source and by feeding nitrogen gas in the deposition system. A composite Mo-N/Cu coating was deposited by operating both Mo and Cu arc sources in the nitrogen atmosphere. Mo-N/Cu coating was deposited on top of a MoN base layer.

The structure of the Mo-N and Mo-N/Cu coating was analyzed by x-ray diffraction (XRD). The XRD patterns of the Mo-N and Mo-N/Cu coatings are shown in Figures 20 and 21 respectively. The XRD peaks corresponding to the steel substrate (S) are marked. Comparison of the d values of the observed XRD peaks with that of the known phases of Mo-N, indicated that the Mo-N coating has structure similar to that of Mo_2N (or $Mo_{16}N_7$) and the Mo-N/Cu has a mixed phase structure of Mo_2N (or $Mo_{16}N_7$) plus MoN.

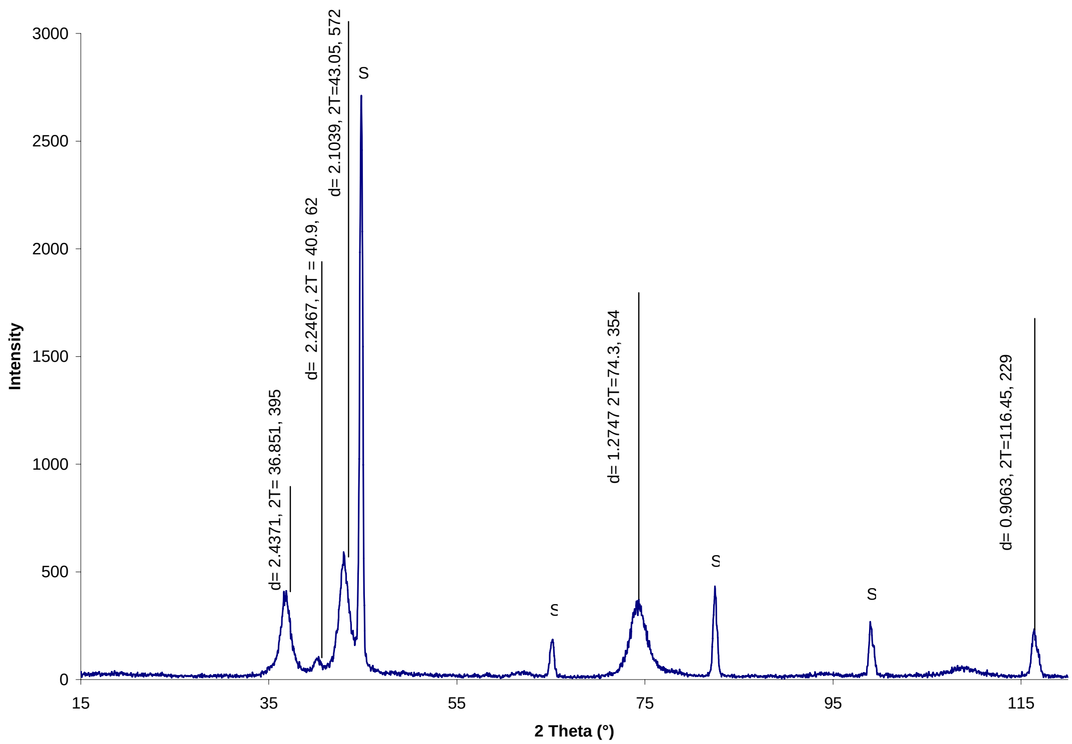


Figure 20. X-ray diffraction pattern of Mo-N coating on steel disc. The peaks corresponding to steel disc are marked (S).

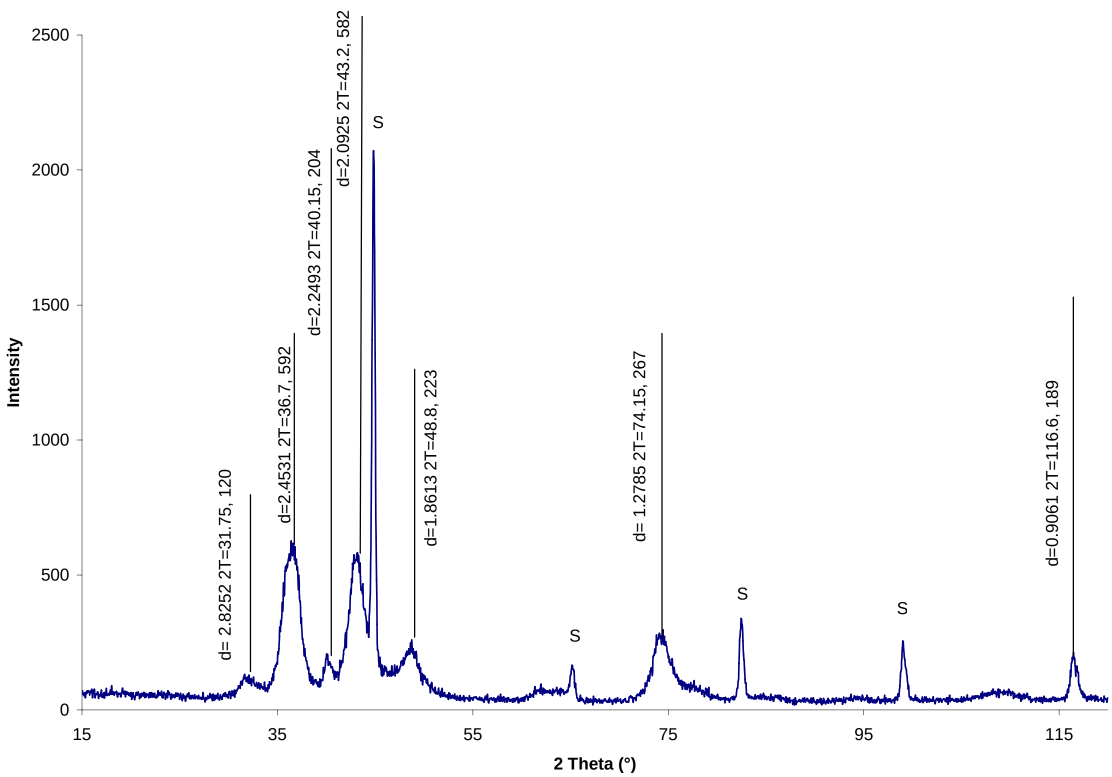


Figure 21. X-ray diffraction pattern of Mo-N/Cu coating on steel disc. The peaks corresponding to steel disc are marked (S).

The grain size of the Mo-N and Mo-N/Cu coatings was calculated based on the full width at half maximum of the XRD peak at 2-Theta at 36.851 for Mo-N and 2-Theta at 36.601 for Mo-N/Cu and found to be ~ 12nm and 7nm respectively. Thus it appears that the introduction of Cu into the Mo-N has reduced the grain size.

The nanohardness of the Mo-N and Mo-N/Cu coating was measured and found to be 19 GPa and 29 GPa respectively. Higher hardness of the Mo-N/Cu coating could be related with the smaller grain size. It is anticipated that the overall hardness of the MoN based coatings can be further enhanced by obtaining single phase coatings.

2.5.4 TiN-SiN Coating

In this Phase II program yet another composite coating viz. TiN-SiN was developed. TiN coatings are widely used in wear protection for cutting tools and various mechanical components. It has been shown that the failure mode of the TiN coatings in machining application is related to the initiation and propagation of cracks at the columnar grain boundaries [9,10]. In a related study, it has been reported that the use of amorphous SiN at the grain boundaries can suppress the propagation of cracks and therefore enhance the useful life of the TiN coating [11]. It has also been reported that a nanocomposite TiN-SiN can attain very high hardness (> 50 GPa) and is resistant against oxidation in air up to 800°C. Thus we decided to develop TiN-SiN coating utilizing large area filtered arc deposition technique for machining application.

The following procedure was used for developing TiN-SiN coatings. Highly polished steel discs were thoroughly degreased ultrasonically in blue gold and isopropanol and blow dried in nitrogen. The cleaned discs together with few Si pieces were loaded in the large area filtered arc deposition (LAFAD) system and the system was evacuated to a base pressure of ~ 10^{-3} Pa. Initially the substrates (steel disc, Si) were sputter cleaned in Ar plasma. A metallic bond (Ti) coating was deposited on top of the sputter-cleaned parts. TiN-SiN coating was deposited by operating two Ti arc sources and one Si arc source in nitrogen atmosphere. For comparison purpose TiN coating was also deposited under identical conditions.

The structure of the TiN-SiN coating was analyzed by x-ray diffraction (XRD) and compared with that of TiN. The XRD patterns of the TiN and TiN-SiN coatings are shown in Figures 22a and 22b respectively. The XRD peaks corresponding to the TiN phase are marked. The remaining peaks are due to the steel substrate. No discernible peaks corresponding to Si-N phase was observed in the XRD pattern of TiN-SiN (Figure 22b), indicating amorphous nature of the Si-N phase, if present. In the XRD pattern of TiN (Figure 22a), the intensity of the 111 reflection of TiN is found to be higher than that of 200 reflection, indicating slight 111 texture. On the other hand, in the XRD pattern of TiN-SiN (Figure 22b), the intensity of the 200 peak of TiN is much higher than that of 111 peak of TiN-SiN coating indicating a strong 200 texture of TiN-SiN coating. Similar 200 texture of the TiN-SiN coating was also observed on the Si substrate. Based on these observations it appears that the texturing of TiN-SiN coating is intrinsic to the process/composition and does not depend upon the substrate. The mean nano-hardness of the TiN-SiN coating was determined and found to be higher viz. 39.4 GPa compared to that of TiN viz. 27.8 GPa. It should be mentioned that there was variation in the nano-hardness value from one place to the other in the coating. It was conjectured that the variation in the nano-hardness could be related with variation in Si concentration in the coating. The uniform distribution of Si in the coating can be achieved by scanning the Si arc plasma. It is anticipated that the TiN-SiN composite coating with higher hardness will provide higher tool life in machining application.

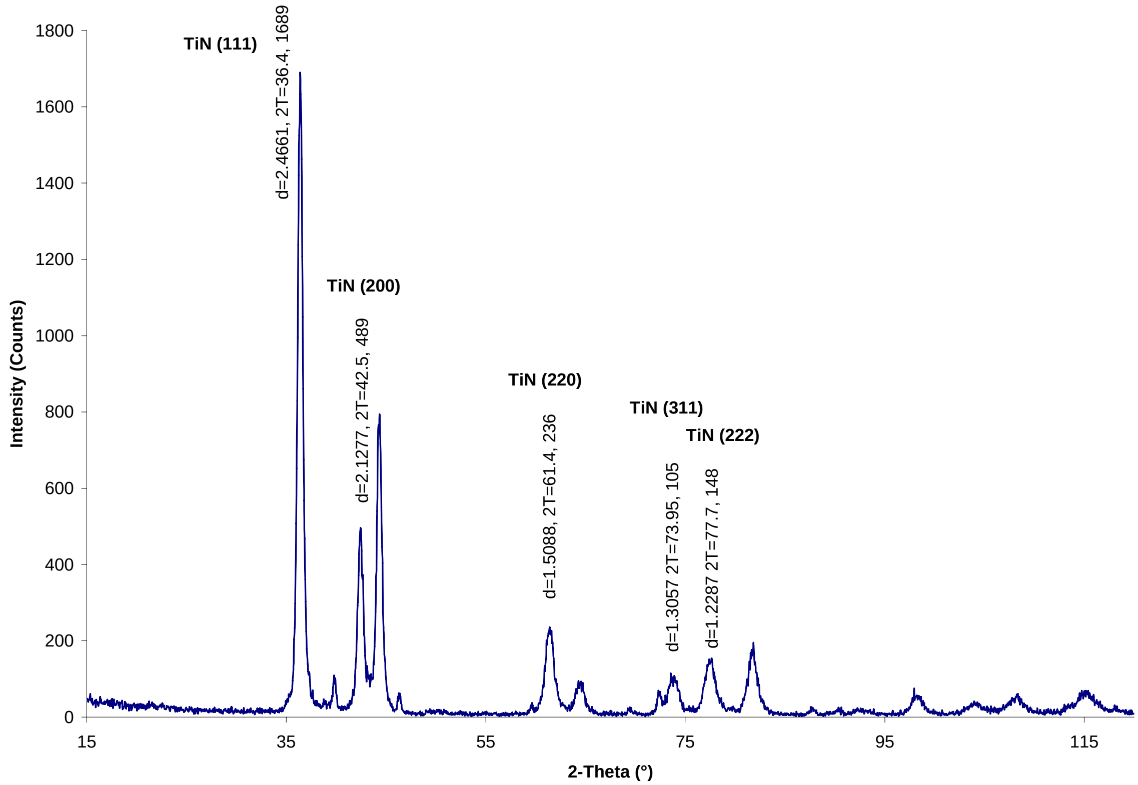


Figure 22a. X-ray diffraction pattern of TiN coating.

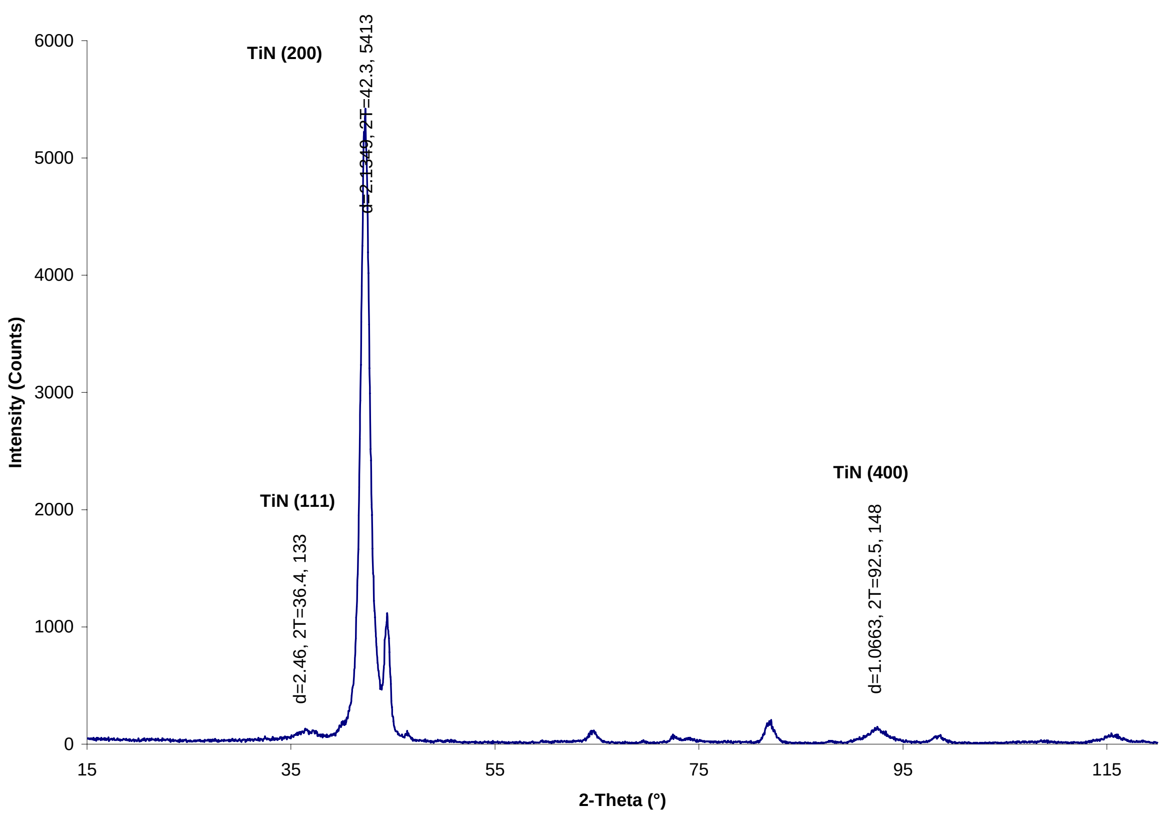


Figure 22b. X-ray diffraction pattern of TiN-SiN coating.

2.6 COMMERCIALIZATION EFFORT

2.6.1 Coating for Orton Ceramic

Orton Ceramics of Westerville, OH utilizes steel punches, in a pair (upper/lower), to press hard ceramic powders. Chrome plating is currently being used to enhance the life of the punches. Orton Ceramic was interested in developing other coatings to further enhance the life of the punches. In this program, UES has evaluated the performance of various hard coatings viz. TiN based, TiAlN and CrN based. The photographs of some of the Orton punches coated with various coatings are shown in Figure 23. Among the punches coated with various coatings, the punches coated with CrN based coating performed the best. The punches coated with relatively thinner CrN based coating lasted for 15000 cycles whereas currently used chrome plated punches lasted for only 10000 cycles. Thus the CrN based coating was able to enhance the punch life by 50% over that of the chrome plating.

In an attempt to further improve the life of the Orton punches, relatively thicker (50% thicker) coating was deposited. The upper punches were run for over 14,100 cycles before they were pulled off due to appearance of wear along the sides and the top edge. At this point in time no sign of wear was found on the lower punches. The upper punches were replaced by new punches coated with current hard chrome and the pressing operation was continued with the same lower punches. The lower punches lasted for over 22,000 cycles before they were pulled off due to pitting and wear. Based on the number of cycles, it was estimated by Mr. Tom McInnerney of Orton Ceramic that life of the upper and lower punches was improved by 50 and 100 % respectively over that of the currently used hard chrome coating. The difference in the life enhancement of upper and lower punches could be related with the travel of the upper punches vs. lower punches. The upper punch moves completely out of the die to allow for ejection of the parts. On the other hand lower punches stay inside the die and do not travel as far through the pressing stroke.

Figure 23. Punches coated with two different sets of coatings.

2.6.2 Coating for Titanium Machining (Kennametal)

Titanium (Ti) and its alloys represent one of the most difficult materials to machine. Ti is a poor thermal conductor. Heat generated during cutting does not dissipate through the parts, chips, and the machine table but tends to concentrate in the cutting area. At higher cutting temperature, Ti is very reactive and therefore has the tendency to weld to the cutting tool leading to tool failure. Due to higher cutting temperature and chemical reactivity, frequent tool replacement is required that increases the machine down time. To achieve reasonable tool life, Ti machining is usually done at lower cutting speed (< 50 m/s) which in turn requires longer production time. Longer production time and increased down time increased the cost of manufactured Ti components.

A multifunctional coating architecture was developed for enhanced Ti machining. The coating architecture and the chemistry were selected to impart higher wear resistance and reduced chemical reactivity between tool/chip and Ti. The machining performance of a carbide insert coated with the multifunctional coating was evaluated in a turning operation of Ti6Al4V alloy. The turning conditions are listed In Table 8. The average wear of the coated and uncoated carbide tools is shown in Figure 24. It is clear that the developed coating reduced the tool wear by more than 50% over that of the uncoated tool.

Table 8. Ti Machining Test Conditions

Insert Type:	CNMG 433; Grade 883 (Chip Breaker MR-4)
Insert Holder Type:	DCLNL 164D
Cutting Speed:	300 sfpm
Feed Rate:	0.008 ipr
Depth of Cut:	0.020 inch
Cutting Fluid:	CIMCOOL 1070 (Concentration - 7% by Vol.)

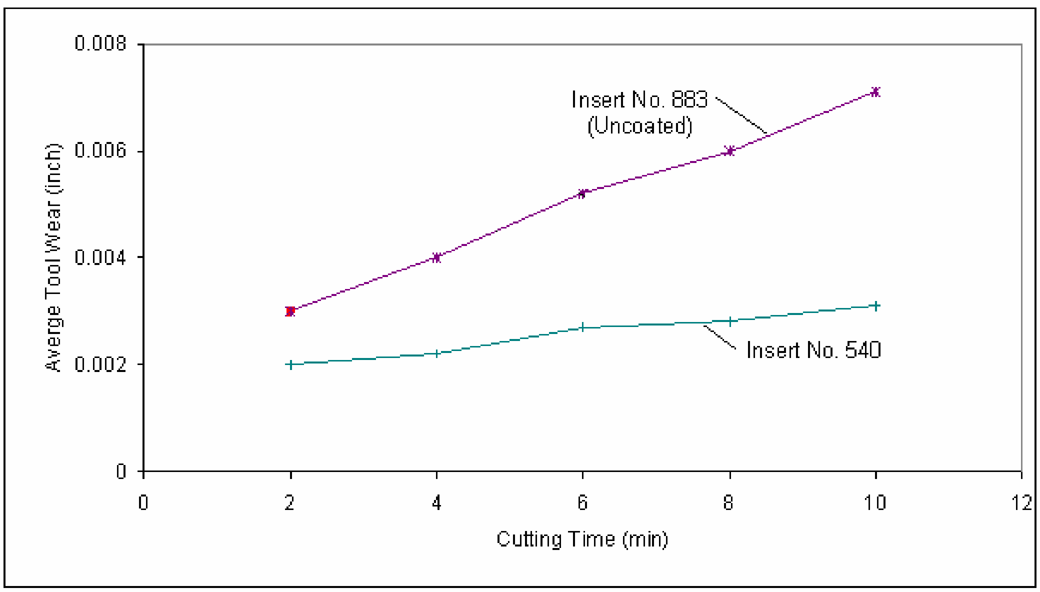


Figure 24. Average tool wear while turning Ti6Al4V work-piece material using one uncoated and four different types of coated inserts.

In this program the performance of the multifunctional coating was further evaluated at Triangle Precision Inds and Kennametal. The multifunctional coating was deposited on carbide inserts obtained from Triangle Precision Inds. The machining performance of the coated inserts was evaluated in Ti machining operation at Triangle precision and compared with that of a commercial coating. The machining parameters and the number of parts produced by inserts are shown in Table 9. The UES coating produced roughly two times more parts than the commercial coating.

Table 9. Titanium Machining Conditions for the Inserts Coated with UES and Commercial Coatings.

	Insert Coating	
	UES	Commercial
Speed (SFM)	250	250
Feed	0.020	0.020
Depth of Cut	0.025	0.025
No. of Parts Produced	5 to 7	2 to 3

The machining performance of the multifunctional coating was also tested at Kennametal. Two different coating configurations, viz. Titan coat A and Titan coat B, were deposited on the tools supplied by Kennametal. The testing was done in a turning operation of Ti6Al4V. The testing parameters are given in Table 10. The relative tool life of the coated and uncoated (control) tools is plotted in Figure 25. It is clear that the coating configuration A almost doubled the tool life whereas the configuration B provided slightly better tool life than the control (uncoated) tool.

Table 10. Testing Parameters

Workpiece	Ti6Al4
Operation	Turning
Coolant	Flood
Machine	Boehringer
Conditions	High Speed

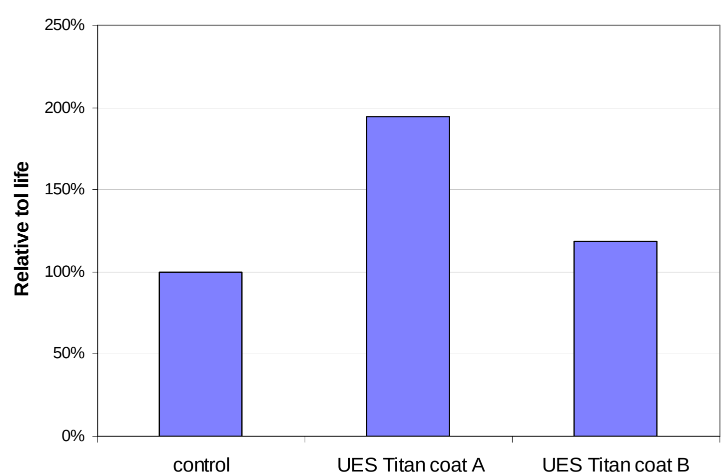


Figure 25. Relative tool life of coated (TitanCoat A, TitanCoat B) and uncoated (control) tool in a turning operation.

2.6.3 Coating on Delphi Parts

In a meeting between Delphi, EMTEC and UES, few parts of the automotive breaking systems were identified for potential coating application.

Ball screws and gear systems are part of the automotive breaking assembly manufactured by Delphi. The ball screws consist of two parts viz. an outer part called nut and an inner part called screw. The inside of the nut and the out side of the screw are major functional surfaces. These surfaces are identified as the major functional areas of the ball screw that may require lubricous coating for enhanced performance.

In this program fixtures were designed and built to hold the inner and outer rings of the ball screws and the gears inside the LAFAD system. Two Ti arc targets were installed in the filtered arc sources of the LAFAD system. The gears and the ball screws obtained from Delphi were thoroughly degreased ultrasonically in blue gold and isopropanol and blow dried in nitrogen. The cleaned parts were loaded in the LAFAD system and the system was evacuated to a base pressure of ~ 10^{-3} Pa. Initially the parts were sputter cleaned in Ar plasma. A metallic bond coat of Ti was deposited on top of the sputter cleaned pares. A TiC+C coating was deposited followed by the diamond like carbon (DLC) coating. The coating deposition was done at 200°C. A photograph of the DLC coated screws of the ball screws is shown in Figure 26. The coated parts were delivered to Delphi for evaluation.

Figure 26. Ball screws coated with carbon based coating.

2.6.4 Coating on Arius Eickert Parts

In this program a contact was made with Arius Eickert located in Fremont, OH through the help of EMTEC (Mr. Percy Gros). Arius Eickert is a manufacturer of scissors, shears and other manicure and household related products. After discussions with the president of Arius Eickert, Mr. Uwe Eickert, it was decided to do two different colored coatings namely gold and black. Appropriate fixtures were developed to hold the scissors in the LAFAD chamber. TiN and DLC coatings were deposited on the highly polished scissors with gold and black colors. The coated scissors are shown in Figure 27. More scissors were coated with black color coating. All the coated scissors were sent to Arius Eickert for evaluation. According to Mr. Uwe Eickert, the initial test data was very encouraging. One of the issues was the coating cost.

Figure 27. Photograph of the gold and black colored coatings on scissors.

2.6.5 Coating on Nucor Parts

EMTEC provided a contact to the Nucor Corp, Charlotte, NC a steel company. Nucor uses rollers as edge guide on a reversing cold mill. Nucor was interested in increasing the wear life of the rollers. In this program one of the Nucor rollers was coated with hard wear resistant coatings and sent it back to Nucor for performance evaluation. By mistake the coated roller was machined before use and therefore could not be evaluated. Attempts are currently being made to renew the contact with Nucor to continue coating Nucor rollers.

2.7 FABRICATION OF FIXTURES

For successful commercialization of the coatings developed in this program, the throughput of the deposition system should be high. In this program time was also spent in designing and fabricating the fixtures to hold large number of tools in one deposition run. Specific fixtures were developed to hold the parts obtained from Delphi, and Arius Eickert. The photographs of some of the fixtures are shown in Figure 28.

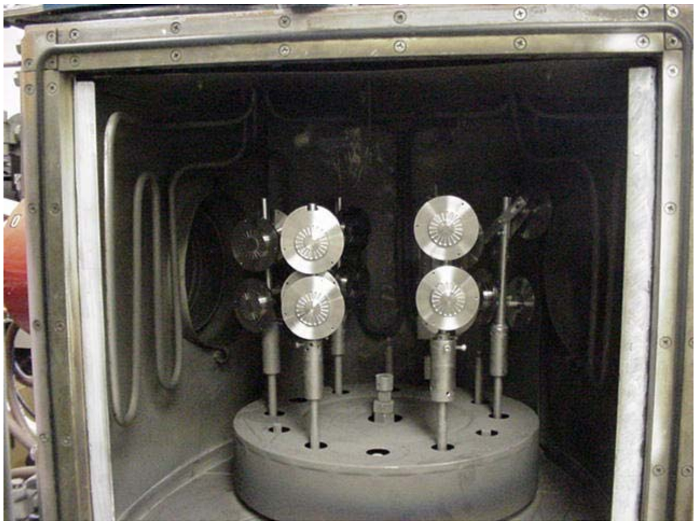


Figure 28. Photograph of coated dies mounted on the fixtures made at UES.

2.8 SAVINGS AND COST ANALYSIS

One of the purposes of this program was to reduce cost reduction in the manufacturing operation. In this program a study was conducted at Thaler Machine Company (Mr. Mike Martin), an industrial partner. In this study perishable tooling cost savings was estimated by using coated carbide tooling vs. uncoated carbide tooling in the then current production jobs at Thaler Machine Co.

This study is based on measured tooling life increases when using coated tools over uncoated tools in two key production jobs at Thaler Machine Company. The study covered a seventeen-week period (8 weeks with uncoated tools and 9 weeks with coated tools). The charts shown in Figure 29 indicate two elements of each job. First element is production volume measured in the quantity of parts shipped weekly. The second element is perishable tooling cost required to make each part. The tool cost savings is evident when reviewing the perishable cost charting. Beginning week number 9, coated tooling was substituted for uncoated tooling.

- The Average Tooling Cost for Part “A” during the Uncoated phase of the study was $0.23 per part.
- The Average Tooling Cost for part “B” during the Uncoated phase was $1.47 per part.
- The Average Tooling Cost for part “A” during the Coated phase was $0.13 per part.
- The Average Tooling Cost for part “B” during the Coated phase was $0.86 per part.

That yields a per part cost savings of $0.10 on Part “A” and $ 0.60 on part “B”. Thus over 40% cost savings can be achieved by coating the cutting tool in actual production job.

To put this in perspective, if we multiply the $0.10 per part savings on part “A” by the whole seventeen week volume that adds up to $ 102,442.10. On part “B” the saving was $ 46,300.00.

It was estimated by Mike Martin in his machining operation, the cost savings that could be realized by using coated over uncoated tooling on his tough to machine projects could be as high as $ 437,000.00 annually if everything else remains the same as in our study.

It should be mentioned that the enhanced tool life due to the developed coatings would also minimize the downtime of the machining operation and therefore provide more savings. Savings related to the less down time was not considered in the aforementioned analysis at Thaler Machine Company.

Cost of the coatings depends on the size and geometry of the tools that required coating. For a given coating material, a deposition run using the LAFAD system has a fixed cost. Thus the coating cost per tool (part) depends upon the number of tools that can be accommodated in a single deposition run. The currently available coating deposition (LAFAD) system at UES has limited coating zone viz. 13 inch (dia.) x 12-inch height that limits the number of parts that can be accommodated in a single deposition run. A larger deposition chamber can accommodate more parts and therefore the coating cost per part can be reduced. For example in the existing LAFAD chamber about seventy to eighty half-inch diameter and about 3 to 3.5 inch long end mills can be accommodated in one deposition run. The cost of coating developed in this porcess per end mill will be ~ $15.00 .

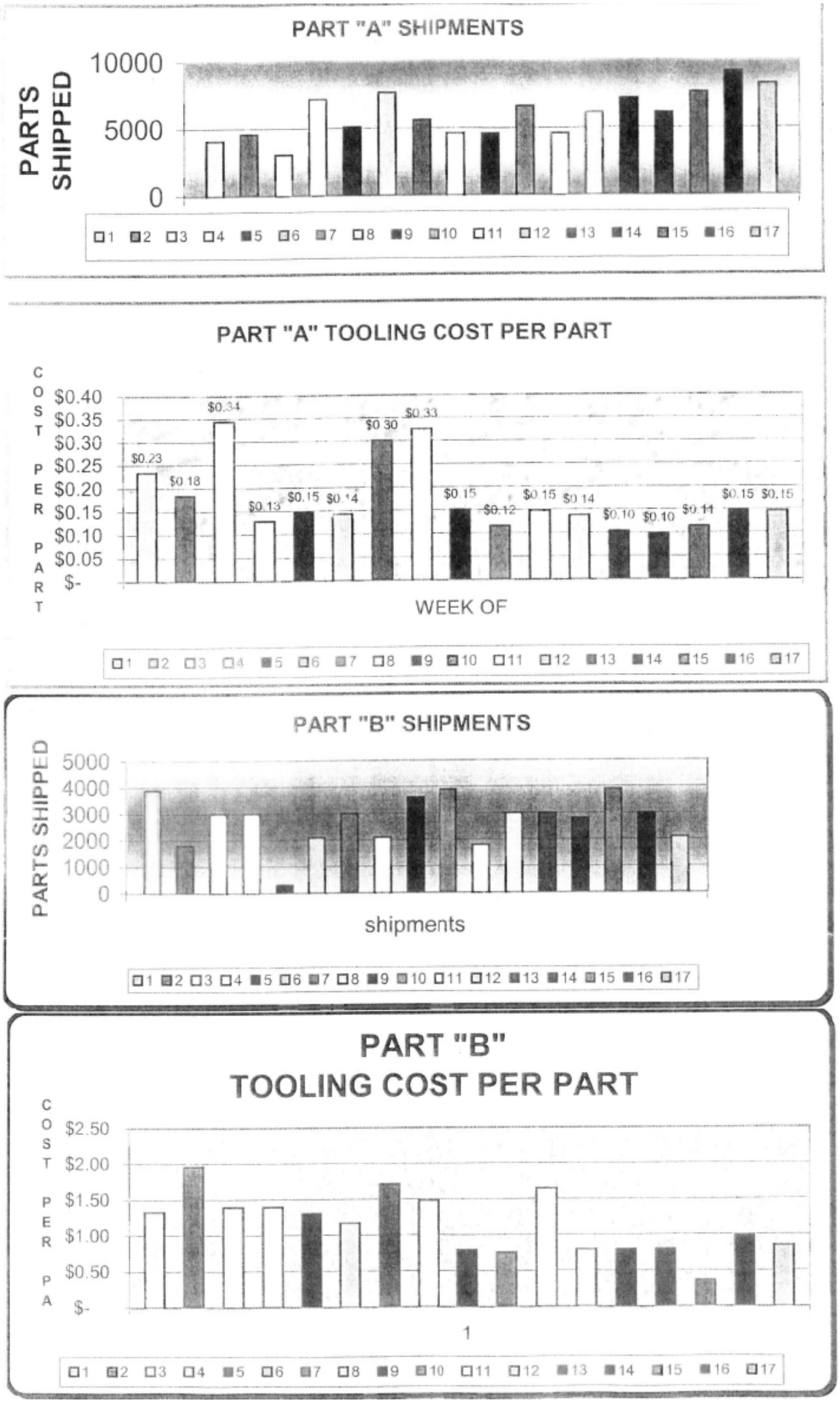


Figure 29. Analysis of cost savings with coated tools.

The cost of a 4 flute 0.5 inch diameter uncoated carbide end mill is ~ $30.00, while the cost of a standard TiN coated tool of the same size is $35.00 [12]. Thus the cost of TiN coating for the end mill is $ 5.00, which is much lower than our cost ($ 15.00). By having a deposition chamber that can accommodate more parts in a single deposition run, the coating cost can be lowered. However, it will still be difficult to bring the cost of UES's new coatings down to a level that will be competitive with current market prices, even though in many instances UES coatings performed better than commercial coatings.

3.0 CONCLUSIONS

The purpose of the EMTEC CT-77 program was to utilize a state-of-the-art commercially viable large area filtered arc deposition (LAFAD) system to develop coatings for enhancing tool life in various machining operations. During Phase I and Phase II part of the program, various hard, hard-soft and composite coatings were developed and characterized. The machining performance of the developed coatings were evaluated in actual commercial production runs and compared with that of uncoated and also with tools coated with commercially available coatings. Significant improvement in the tool life was demonstrated. Specific coatings were designed to enhance the machinability of the hard to machine materials such as titanium and nickel based (Hastealloy) alloy. Again considerable improvement in the tool life was demonstrated.

In the Phase II program, with the help of EMTEC, considerable efforts were made to commercialize the coatings developed at UES. In this endeavor, contacts were made with the following companies: Orton Ceramic, Westerville, OH, Delphi, Dayton, OH, Arius Eickert, Fremont, OH, Nucor Corporation, Charlotte NC and Kennametal, Latrobe, PA. The performance of a few of the coatings developed in this program was evaluated in the production runs of some of these companies and compared with the coatings currently being used. The coatings developed in this program exhibited better performance.

As described in Section 2.8, the cost of commercial coatings is lower compared to that of UES coatings. The cost of UES coating can be lowered by upgrading the deposition chamber with a larger deposition area.

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